Inventering av framtidens el- och värmeproduktionstekniker

Delrapport Energilagring

Elforsk rapport 08:83

Lars Messing och Sture Lindahl

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ELFORSK

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Förord

Fokus för hela projektet avseende inventering av framtidens produktionstekniker för el- och värmeproduktion har varit framtida möjlig utveckling av olika produktionstekniker för kraft- och värmeproduktion med bedömning av prestanda samt när en eventuell implementering och kommersialisering kan vara möjlig. Att kunna göra en sådan bedömning är av största vikt för att kunna planera inför kommande förändringar och investeringar och när dessa kan komma, men också för att kunna sätta in de FoU-resurser som erfordras.

Projektet har genomförts som olika deluppdrag inom de olika produktionsområdena med föreliggande rapport avseende delrapport Energilagring. Lars Messing, Gothia Power AB, har varit projektledare för delstudien. Alla övriga delrapporter inom projektet samt en syntesrapport återfinns för nedladdning på Elforsks hemsida www.elforsk.se.

Projektet har finansierats av AB Fortum Värme samägt med Stockholms stad, E.ON Värmekraft AB, Jämtkraft AB, Kraftringen Produktion AB, Mälarenergi AB, Skellefteå Kraft AB, Umeå Energi AB, Vattenfall AB, Öresundskraft AB samt av Statens Energimyndighet.

Projektet har följts av en styrgrupp bestående av Björn Fredriksson Möller och Mikael Palmgren E.ON Värmekraft, Sten Grahn Fortum Värme, Anders Johansson och Svante Söderholm Statens Energimyndighet, Maria Jonsson och Leif Liinanki Vattenfall Research and Development, Ulf Lindqvist Jämtkraft, Magnus Stenvall Umeå Energi samt Lars Wrangensten Elforsk.

Elforsk tackar styrgruppen för värdefulla synpunkter och uppslag.

Lars Wrangensten
Elforsk AB
Programområde El- och Värmeproduktion
December 2008

Sammanfattning

I denna rapport görs en genomgång av olika tekniker för lagring av elenergi. Följande lagringstekniker beskrivs med avseende på metod, egenskaper, potential och ekonomi.

- Batterier
- Kondensatorer
- Svänghjul
- Pumpkraftverk
- Vätgasgenerering
- Luftkomprimering

Angående metoder för energilagring görs följande värderingar:

- Batterilagring: Utvecklingen av Litium-jon batterier är intressant. I dagsläget är det svårt att se energilagring i batterier som ett bra alternativ i applikationer med ofta förekommande omladdningscykler och stora energimängder som omladdas. Den begränsade livslängden och effektbegränsning vid in- och urladdning är begränsande.
- Energilagring i kondensatorer: ”Super-kondensatorer” med stor effektkapacitet bedöms vara intressanta för applikationer där snabb effektreglering är nödvändig. I samband med utveckling av kondensatorer baserade på kol-nanorör ökas energilagringskapaciteten betydligt och därmed kan detta bli ett alternativ till batterilagring. Vidare är det kombinera batteri- och kondensatorlagring för att få längre livslängd för de laddningsbara batterierna och snabbare effektreglering.
- Energilagring i svänghjul: Energilagringskapaciteten är relativt begränsad medan effektregleringen kan ske snabbt. Därmed kan detta system vara jämförbart med energilager baserat på kondensatorer.
- Energilagring i pumpkraftverk: Detta system är väl lämpat och beprövat för energilagring i tidsskalan ett eller några dygn. I det svenska kraftsystemet finns ännu inte så stort behov för energilagring i denna tidsskala eftersom andelen reglerbar vattenkraft är stor. Dock kan man tänka sig att pumpkraftverk i södra Sverige kan användas för att avlasta kraftnätet i vissa driftlägen och därmed kan behovet att bygga nya kraftledningar minskas.
- Energilagring med vätgas: Hantering av vätgas i stor skala anges som ett problem.
- Energilagring med luftkomprimering: Denna metod är kombinerad med gasturbinanläggningar där man under perioder med effektöverskott komprimerar luft för att använd senare i gasturbinkraftverk (i stället för kompressor). Denna teknik bör övervägas i framtiden om man planerar att bygga nya gasturbinkraftverk i Sverige. Det bedöms dock att behovet av detta är litet i nuläget.

Olika användningsområden för den upplagrade energin diskuteras, såsom:

- Förbättring av elkvalitet
- Förbättring av transient stabilitet
- Dämpning av elektromekaniska pendlingar i kraftsystemet
- Momentan aktiv störningsreserv
- Frekvensreglering
- Snabb aktiv störningsreserv
- Produktionsoptimering
- Ökning av överföringsförmåga

Inom forskningsvärlden pågår teknikutveckling inom områdena batterier, kondensatorer med mycket stor kapacitans, svänghjul med mera. Eftersom utvecklingen är snabb och denna rapport endast ger en översiktlig bild av forskningen inom området finns behov av att kontinuerligt följa teknikutvecklingen.

Bedömningen görs att det i Sverige främst finns behov av att utvärdera nyttan av elenergilagring i olika applikationer och att identifiera lämpliga metoder för energilagring för de olika applikationerna.

Utifrån förutsättningar och behov i Sverige och i Norden bör forsknings- och utvecklingsinsatser göras enligt följande:

Identifiera områden där det finns behov av åtgärder och förbättringar i kraftsystemet.

Utgående från identifierade behov utreds sedan om elenergilagring kan vara användbart för att ge de förbättringar som krävs.

För varje applikationsområde utvärderas sedan olika elenergilagringsalternativ beträffande tekniska möjligheter, miljöpåverkan och ekonomi.

Under de närmaste åren (2 till 4 år framöver) bör konceptuella lösningar tas fram för de olika applikationerna där elenergilagring bedöms vara tekniskt och ekonomiskt gångbara och där applikationerna fyller nya behov i kraftsystemet som beror på ökad mängd distribuerad generering (till exempel vindkraft), ökad elenergianvändning beroende på nya belastningsobjekt (elbilar), förändring av distributionsnätens uppbyggnad, mm.

Bedömning av olika koncept för att gå vidare med pilotprojekt görs så snart det är möjligt med hänsyn till ovan beskrivna konceptuella studier. Prioritering för genomförande görs.

Inom cirka 5 år från nu inleds förverkligande av pilotprojekt. Genomförandetiden för dessa varierar troligen betydligt mellan olika tekniklösningar.

Utvärdering av pilotprojekt görs så snart det är möjligt, med målet att vidare implementering kan ske inom 10 år.

Summary

In this report a survey of different techniques for storage of electrical energy. The following alternatives are described regarding method, characteristics, potential and economy.

- Batteries
- Capacitors
- Flywheels
- Pump storage hydro power plants
- Hydrogen gas generation
- Air compression

Regarding evaluation of methods for storage of electrical energy:

- Battery storage: The development of Lithium-ion batteries are of great interest. In the present situation it is however difficult of classify battery storage as a good alternation in applications with frequent re-charging cycles and re-charging of large energy volumes. The batteries have limited life length compared to other alternatives. Also the power is limited at charging and discharging.
- Energy storage in capacitors: "Super-capacitors" having large power capacity is considered to be of interest in applications where fast control of power is necessary. The ongoing development of based on carbon-nanotubes will increase the energy storage capacity compared with the today existing super-capacitors. This can in the future be an alternative to battery storage. Of further interest is also the idea to combine battery - and capacitor based storage to achieve longer lifetime of the batteries and faster power control.
- Fly-wheel energy storage: The energy storage capacity is relatively limited but power control can be fast. This system can be an alternative to capacitor based energy storage.
- Pump-storage hydro power plant: This type of energy storage is well suited and proven for time frame up to some days. I the Swedish power system there is today not any large demand of energy storage in this time frame as there is a large capacity in conventional hydro power plants with storage capacity. Pump-storage can however be of interest in the southern part of Sweden. In some operation stages the grid is loaded up to its limit due to large power transmission from the north. The pump-storage can reduce this power transfer during critical periods and can therefore be an alternative to new power lines.
- Hydrogen energy storage: The handling (storage and transfer) of hydrogen is considered to be difficult and dangerous.
- Air-compression energy storage: This method is combined with gas turbine plants. During periods with surplus of energy in the power system this surplus energy is used to compress air and store it. This compressed air is used in the operation of gas turbine power plant where

the compressed air is used instead of the normal use where the gas turbine makes the compression. The possibility should be considered in the future if new gas turbine power plants are to be built in Sweden. This is not the situation today.

Different application areas where the energy storage can be used are discussed, such as:

- Electrical supply quality improvement
- Improvement of power system transient stability
- Damping of electromechanical oscillations in the power system
- Spinning disturbance power reserves
- Power system frequency control
- Fast disturbance power reserves (activated within 15 minutes)
- Optimization of energy production dispatch
- Increase of power grid transmission capacity

In the scientific world the technical development is very active within areas regarding batteries, capacitors with very large storage capacity, flywheels, etc. As the progress is very fast and this report gives only a brief survey of the research within the area, there is a need to continuously follow the technical development.

The judgement is done that there is demand for evaluation of the value of energy storage for different applications and to identify suitable methods to be used in the different applications.

Regarding conditions and demands in Sweden and the other Nordic countries research and development activities should be done as:

Identify application areas where there are requirements of improvements in the power system.

From the identified demands it should be analysed if electrical energy storage can be used to achieve the required improvements.

For each application area different alternatives for energy storages are evaluated regarding technical feasibility, environmental influence and economy.

During the next 2 – 4 years conceptual solutions should be presented for application where electrical energy storage is considered to be technically and economically feasible. These applications should be linked to new requirements in the power system due to increased volume of distributed power generation (for example wind power), increased consumptions of electrical energy due to new load objects (for example electrical cars), changed structure of the distribution grids, etc.

Evaluation of the different concepts is done as soon as the above described conceptual studies allow. Prioritization of realization should be done.

Within 5 years from now realization of pilot projects are started. The project time for the different projects will probably vary significantly due to different technical solutions.

Evaluation of the pilot projects are done as soon as possible with the goal for further implementation within 10 years.

Innehåll

1 Inledning

Elforsk har inom programområde El- och Värmeproduktion under hösten 2007 påbörjat en teknikinventering fokuserad på framtida möjlig utveckling av olika produktionstekniker för kraft- och värmeproduktion med bedömning av prestanda samt när en eventuell implementering och kommersialisering kan vara möjlig.

Visionen med projektet är att ta fram troliga utvecklingsscenarier för olika el- och värmeproduktionstekniker samt att kunna visa på de möjligheter som ges vid en implementering samt när denna kan komma. Målet är att identifiera möjliga teknikkliv för olika produktionstekniker i tidsperspektivet 2020/2030. Deluppdrag har genomförts avseende möjlig utveckling för

- Kraftvärmeproduktion
- Vindkraft
- Kärnkraft
- Småskalig distribuerad produktion

Vissa av teknikerna (solceller, vindkraft, vågkraft) producerar el intermittent beroende på tillgång och variationer i den primära energikällan (kännetecknad av solinstrålning, vindhastighet och våghöjd). Hur denna variation stämmer med variationen av elbehovet i elnätet är naturligtvis av största betydelse. Olika typer av reglerkraft exempelvis vattenkraft måste användas för att utjämna skillnaderna mellan möjlig produktion och rådande elbehov. Styrgruppen för projektet har tyckt att det skulle vara av intresse att även få belyst hur utvecklingen av tekniker för energilagring kan komma att inverka och möjligen höja konkurrenskraften för dessa intermittenta produktionstekniker. Föreliggande utredning avser olika möjliga energilagringstekniker i tidsperspektivet 2020/2030.

Målet för detta uppdrag är att i korthet beskriva ett möjligt teknikutvecklingsscenario för området energilagring kopplat till intermittenta produktionstekniker (i första hand vindkraft, solceller och vågkraft) i tidsperspektivet 2020/2030.

Uppdraget föreslås att främst gälla batterier men även andra intressanta tekniker bör tas med såsom väte-/vätgaslagring, avancerade kondensatorer och andra tekniker där teoretiska studier visar på mycket stor utvecklingspotential vad det gäller prestanda/kostnad (jämför utvecklingen inom IT-området). Med IT-liknande avses en trend som skulle kunna göra att utvecklingen av aktuell lagringsteknik kraftigt avviker från basscenariot, det vill säga likt IT-utvecklingen fortsätter med regelbunden dubblerad prestanda/kostnad-kvot de närmsta 10-15 åren. Rimlig lagringskapacitet bedöms vara i dygnsskala eventuellt något längre. För de olika möjliga lagringsteknikerna ska följande beskrivas:

- Teknik, prestanda, miljöegenskaper

- Ange om lagringstekniken bedöms användas för lokal produktion eller tillsammans med nätansluten produktion
- Nuvarande status/utvecklingsläge för området (kortfattat)
- Bedömt FoU-behov fram till kommersialisering och implementering
- Pågående FoU-verksamhet
- Möjligt utvecklingsscenario (tidsskala, uppskalningssteg)

Elforskstudien ”El från nya anläggningar 2007” samt Energimyndighetens långtidsprognos har använts som grund vad gäller el- och bränslekostnader samt övriga förutsättningar.

2 Bakgrund

Elektrisk energi i form av växelström låter sig för närvarande inte lagras i kvantiteter av betydelse för elförsörjningen. Detta faktum gör att elförsörjningen intar en särställning bland tillverkningsindustrierna – elförsörjningsindustrin saknar färdigvarulager. Även lagret av halvfabrikat, rörelseenergi lagrad i turbingeneratoraggregatens roterande delar är mycket litet. Beroende på typen av de infasade aggregaten kan detta energilager variera mellan värden motsvarande 5 och 10 sekunders produktion. Tabell 1 visar den maximala systembelastningen i Nordel-systemet under år 2006, som inträffade den 20 januari klockan 8:00-9:00 (CET).

Tabell 1: Maximal systembelastning i Nordel-systemet under 2006

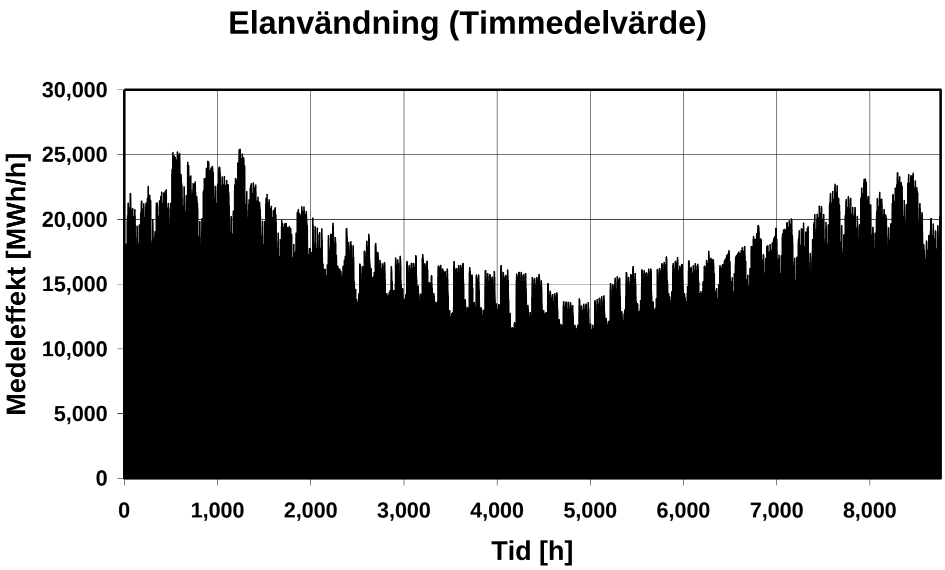
Land	Belastning [MWh/h]
Danmark	5 965
Finland	14 863
Norge	21 368
Sverige	25 743
Nordel	67 939

Vid detta tillfälle var den upplagrade energimängden 95-190 MWh. I praktiken kan endast en mindre del utnyttjas på grund av kravet att nätfrekvensen ska hållas nära 50 Hz. Om nätfrekvensen skulle tillåtas sjunka till 49 Hz, så skulle 3,8-7,6 MWh av den lagrade energimängden kunna frigöras.

I ett växelströmssystem måste det således råda balans mellan tillförsel av mekanisk energi till turbinerna å ena sidan och summan av användning av elektrisk energi och förluster i elförsörjningssystemet å andra sidan. Kostnadseffektiva anläggningar för energilagring kan öka konkurrenskraften hos intermittenta produktionsanläggningar (i första hand vindkraft, solceller och vågkraft). Sådana anläggningar kan även leda till minskning av behovet av upp- och nedreglering av vattenkraftproduktionen. Om anläggningarna för energilagring placeras i södra Sverige kan de eventuellt även bidra till en effektivare utnyttjning av transmissionsnätet.

2.1 Elanvändning

Figur 1 visar elanvändningen timme för timme i Sverige under år 2007 uttryckt som medeleffekt [MWh/h] under var och en av de 8 760 timmarna under året.

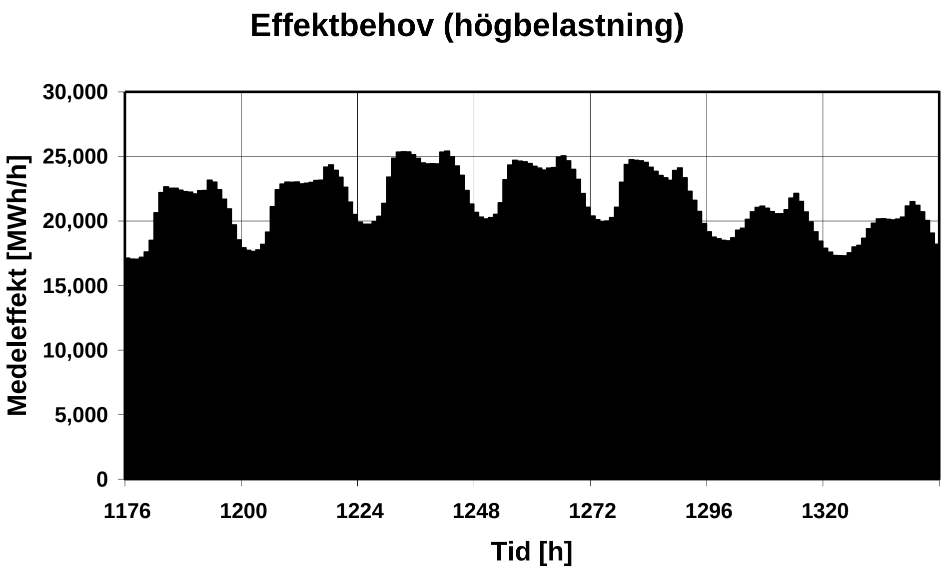


Figur 1: Elanvändning i Sverige under år 2007

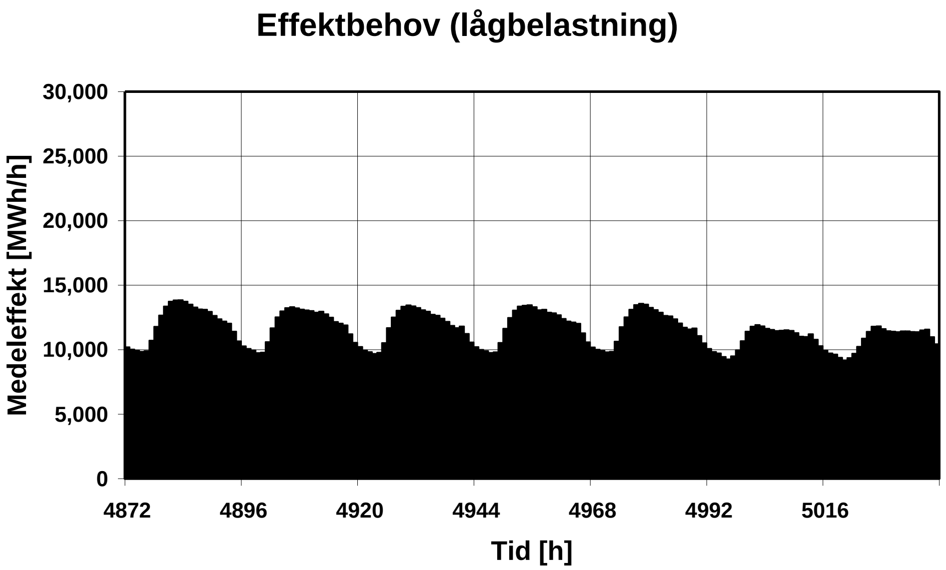
Under år 2007 var den högsta medeleffekten lika med 25 418 MWh/h och detta inträffade 2007-02-21 mellan klockan 18 och 19 (svensk normaltid). Detta dygn var medeleffekten högre än 25 000 MWh/h under fem timmar; tre på förmiddagen och två på kvällen. Detta syns tydligare i Figur 2. Under år 2007 var den lägsta medeleffekten lika med 9 191 MWh/h och detta inträffade 2007-07-18 mellan klockan 03 och 04 (svensk normaltid). Denna natt var medeleffekten lägre än 10 000 MWh/h endast under tre timmar. Detta syns tydligare i Figur 3. Under år 2007 var medeleffekten över hela året lika med 16 097 MWh/h. Variationsbredden (skillnaden mellan högsta och lägsta värdet) är lika med 16 227 MWh/h medan standardavvikelsen är lika med 3 346 MWh/h.

Den största skillnaden mellan två på varandra följande värden på medeleffekten uppgår till 2 282 MWh/h. Elanvändningen uppvisar relativt stabila periodiska variationer under året, veckan och dygnet, vilket gör det möjligt att prognosera den framtida elanvändningen med relativt hög noggrannhet. Prognosfelet för nästa timme är i allmänhet 1 till 2 % av medelvärdet medan prognosfelet för nästa dygn är något större.

Figur 2 och Figur 3 visar elanvändningen timme för timme i Sverige under en höglastvecka och en låglastvecka år 2007 uttryckt som medeleffekt [MWh/h] under var och en av de 168 timmarna under veckan.

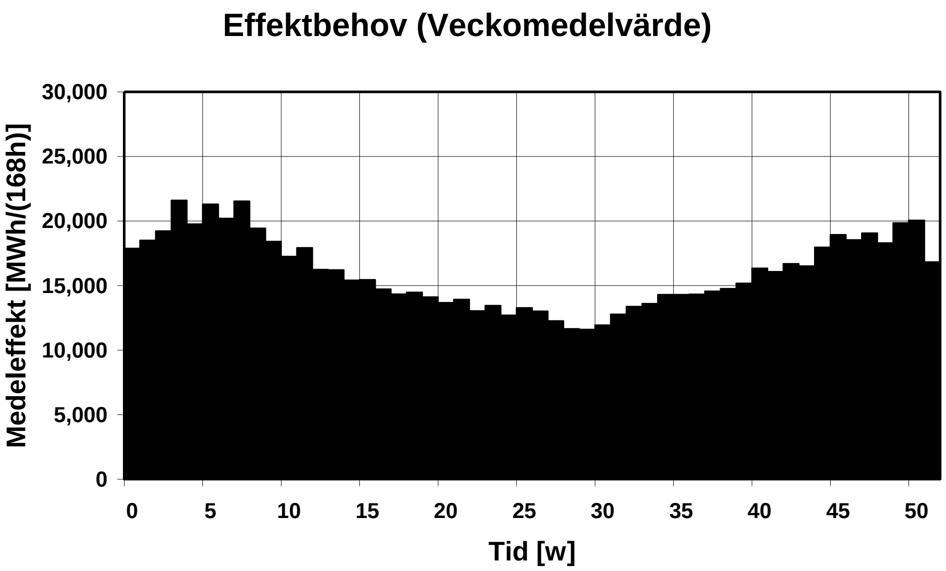


Figur 2: Elanvändningen under en höglastvecka år 2007



Figur 3: Elanvändningen under en låglastvecka år 2007

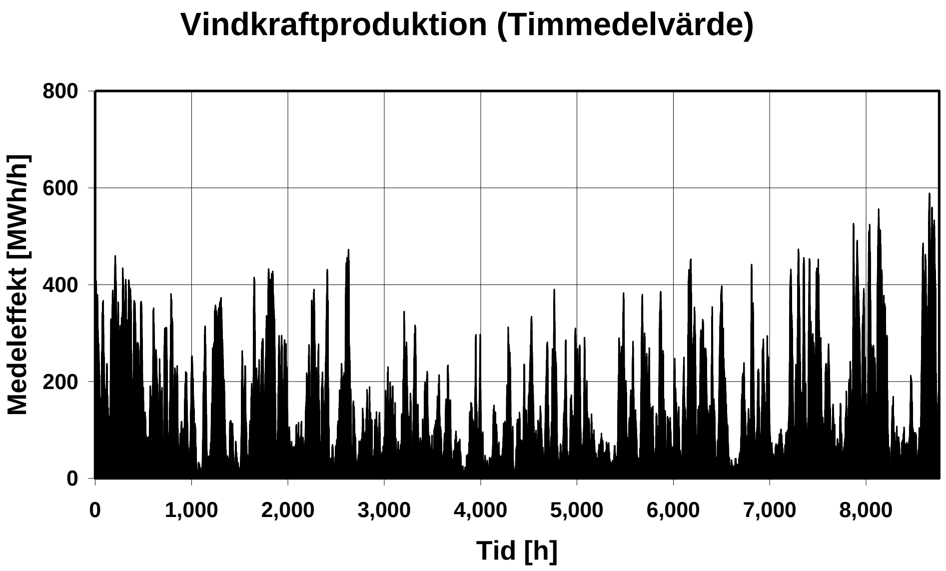
För att särskilja årstidsvariationerna hos elanvändningen från variationerna under veckan och under dygnet har medeleffekten vecka för vecka under år 2007 beräknats, se Figur 4. Den här redovisade medeleffekten är den under veckan använda elenergin [MWh] dividerat med antalet timmar (168 h) under veckan.



Figur 4: Elanvändningens årstidsvariation under år 2007

2.2 Vindkraftproduktion

Figur 5 visar vindkraftproduktionen timme för timme i Sverige under år 2007 uttryckt som medeleffekt [MWh/h] under var och en av de 8 760 timmarna under året.



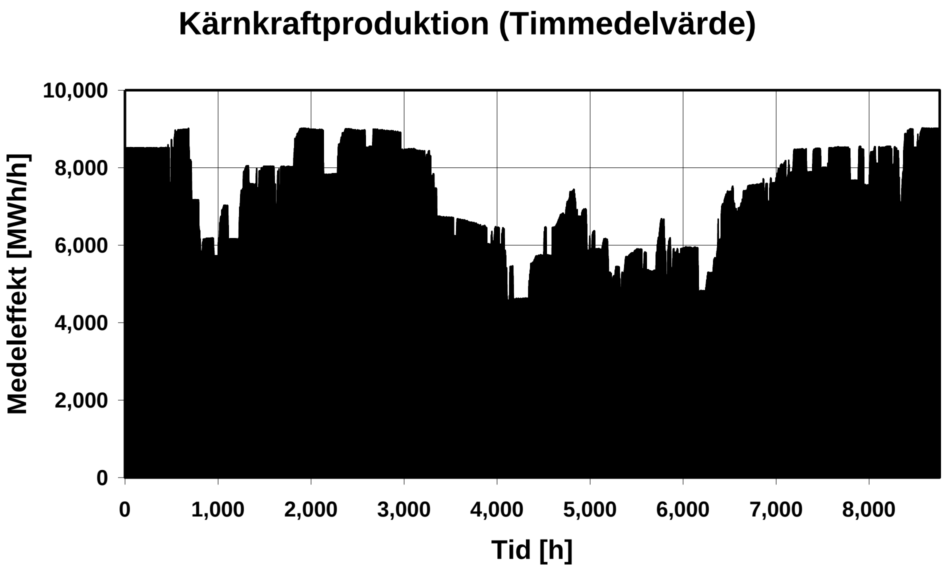
Figur 5: Vindkraftproduktionen i Sverige under år 2007

Under år 2007 var den högsta medeleffekten lika med 589 MWh/h, den lägsta medeleffekten lika med 5 MWh/h och medeleffekten lika med 152 MWh/h. Variationsbredden (skillnaden mellan högsta och lägsta värdet) är lika med 584 MWh/h medan standardavvikelsen är lika med 114 MWh/h.

Den största skillnaden mellan två på varandra följande värden på medeleffekten uppgår till 81 MWh/h. Det pågår utvecklingsarbete i avsikt att få fram metoder att prognosera vindkraftproduktion men de praktiska möjligheterna är fortfarande relativt begränsade.

2.3 Kärnkraftproduktion

Figur 6 visar kärnkraftproduktionen timme för timme i Sverige under år 2007 uttryckt som medeleffekt [MWh/h] under var och en av de 8 760 timmarna under året.



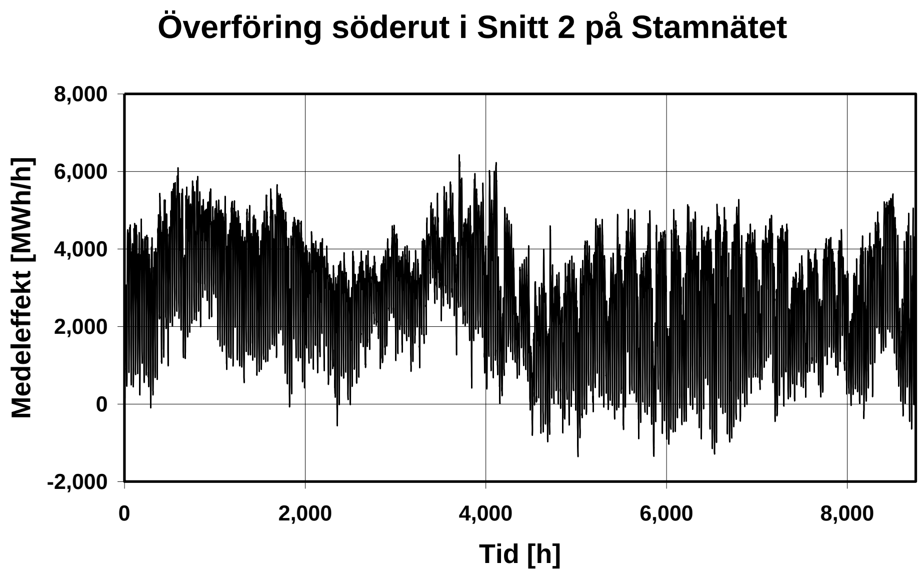
Figur 6: Kärnkraftproduktionen i Sverige under år 2007

Under år 2007 var den högsta medeleffekten lika med 9 024 MWh/h, den lägsta medeleffekten lika med 4 369 MWh/h och medeleffekten över året lika med 7 351 MWh/h. Variationsbredden (skillnaden mellan högsta och lägsta värdet) är lika med 4 655 MWh/h och standardavvikelsen är lika med 420 MWh/h.

Den största skillnaden mellan två på varandra följande värden på medeleffekten uppgick till 807 MWh/h. Bortfall av något av de största kärnkraftaggregaten (Forsmark 3 och Oskarshamn 3) ger upphov till en momentan minskning av kärnkraftproduktionen om cirka 1 200 MW. Anledningen att ändringen av medeleffekten under 2007 är mindre än den installerade effekten är att inget av de största kärnkraftaggregaten kopplades bort omedelbart efter timskarven.

2.4 Överföring på stamnätet

Om anläggningarna för energilagring placeras i södra Sverige kan de eventuellt även bidra till en effektivare utnyttjning av transmissionsnätet. Figur 7 visar överföring i Snitt 2 på Stamnätet under år 2007. Positiva värden innebär att effekten flyter från norr till söder medan negativa värden innebär att effekten flyter från söder till norr. Snitt 2 är en tänkt linje från öst till väst som skiljer norra och södra Sverige när det gäller överföring på Stamnätet.

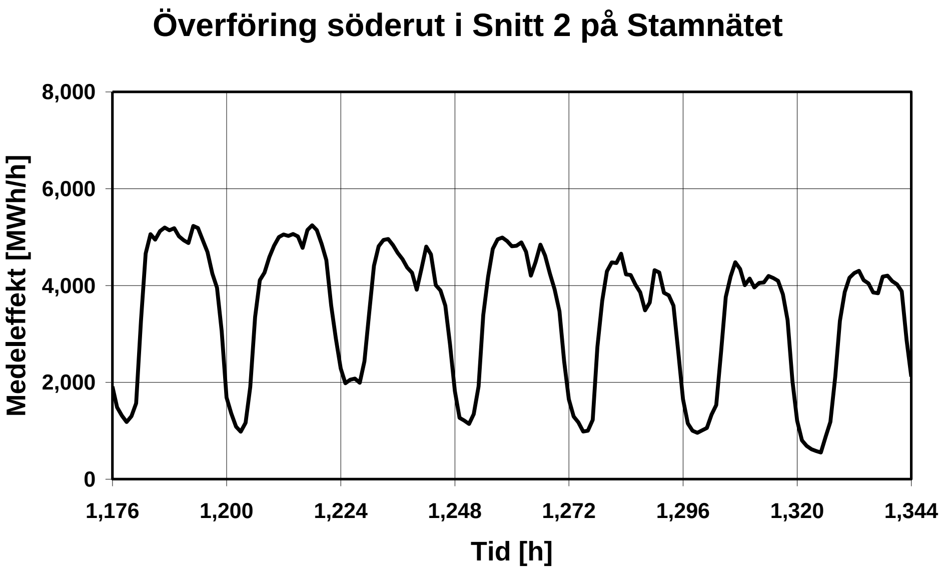


Figur 7: Överföring söderut på Stamnätet under år 2007

Den högsta överföringen från norr till söder på Stamnätet är lika med 6 428 MWh/h och den högsta överföringen från söder till norr är lika med 1 358 MWh/h. Medelvärdet av överföringen på Stamnätet från norr till söder är lika med 2 863 MWh/h. Variationsbredden (skillnaden mellan högsta och lägsta värdet) är lika med 7 785 MWh/h medan standardavvikelsen är lika med 1 517 MWh/h.

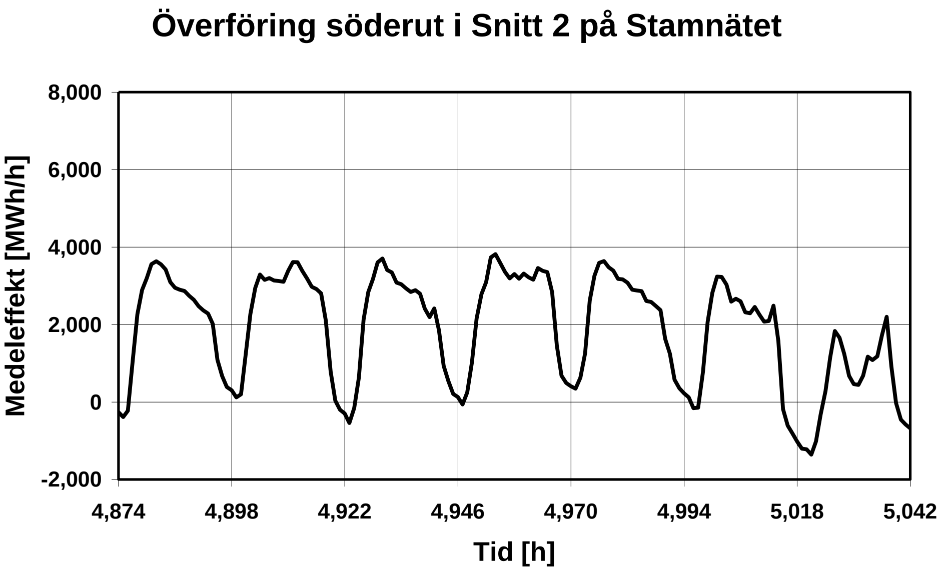
Figur 8 visar överföring i Snitt 2 på Stamnätet under en höglastvecka år 2007.

Den högsta överföringen från norr till söder i på Stamnätet är lika med 5 243 MWh/h och den högsta överföringen från söder till norr är lika med 550 MWh/h. Medelvärdet av överföringen på Stamnätet från norr till söder är lika med 3 437 MWh/h. Variationsbredden (skillnaden mellan högsta och lägsta värdet) är lika med 4 694 MWh/h medan standardavvikelsen är lika med 1 440 MWh/h.



Figur 8: Överföring söderut på Stamnätet under en höglastvecka 2007

Figur 9 visar överföring i Snitt 2 på Stamnätet under en låglastvecka år 2007.



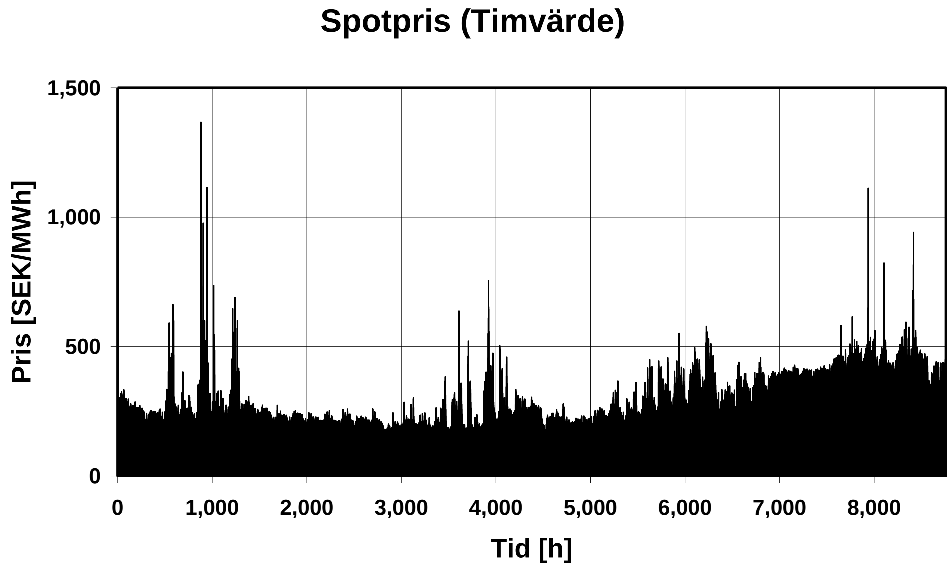
Figur 9: Överföring söderut på Stamnätet under en låglastvecka 2007

Den högsta överföringen från norr till söder är lika med 3 816 MWh/h och den högsta överföringen från söder till norr är lika med 1 358 MWh/h. Medelvärdet av överföringen på Stamnätet från norr till söder är lika med 1 894 MWh/h. Variationsbredden (skillnaden mellan högsta och lägsta värdet) är lika med 5 173 MWh/h medan standardavvikelsen är lika med 1 401 MWh/h.

2.5 Spotpriset

På den avreglerade elmarknaden kan en ägare av en anläggning för energilagring uppnå ett positivt ekonomiskt resultat genom att köpa elenergi när priset är lågt och sälja när priset är högt. Möjligheten att uppnå ett gott ekonomiskt resultat ökar när prisskillnader i systemet ökar. Omfattande installationer av anläggningar torde minska prisskillnaderna och reducera intäkterna för ytterligare installationer av anläggningar för energilagringar.

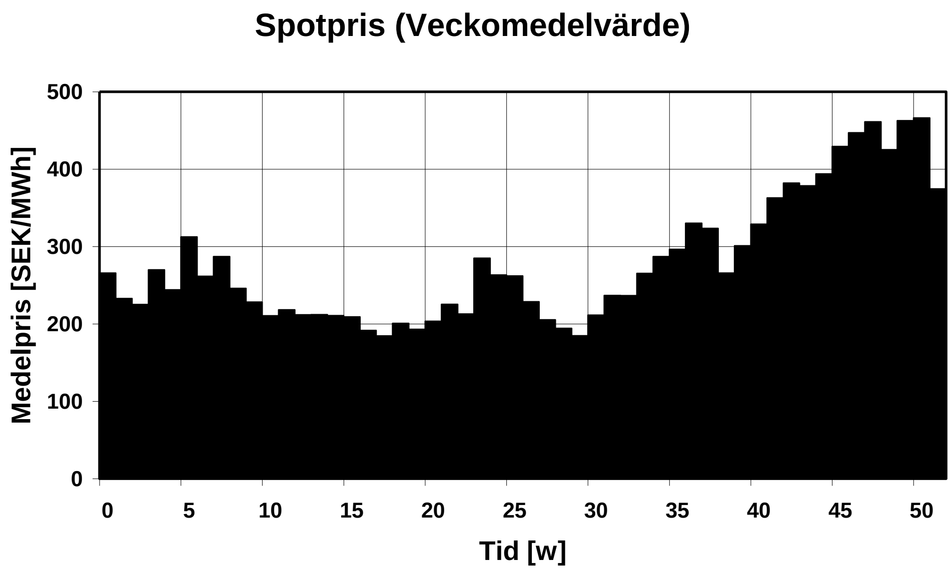
Figur 10 visar spotpriset timme för timme i Sverige (Stockholmsområdet) under år 2007 [SEK/MWh] under var och en av de 8 760 timmarna under året.



Figur 10: Spotpriset i Sverige (Stockholmsområdet) under år 2007

Under år 2007 var det högsta spotpriset lika med 1 367 SEK/MWh, det lägsta spotpriset lika med 38 SEK/MWh och medelpriset lika med 280 SEK/MWh. Variationsbredden var lika med 1 329 SEK/MWh medan standardavvikelsen är lika med 98 SEK/MWh.

Prognoseringen av det framtida spotpriset är av avgörande betydelse för utnyttjandet av anläggningarna för energilagring i driftskedet. Priset uppvisar förutom dygnsvariationer även årstidsvariationer och långsiktiga trender, se Figur 11.



Figur 11: Årstidsvariation för spotpriset i Stockholmsområdet under år 2007

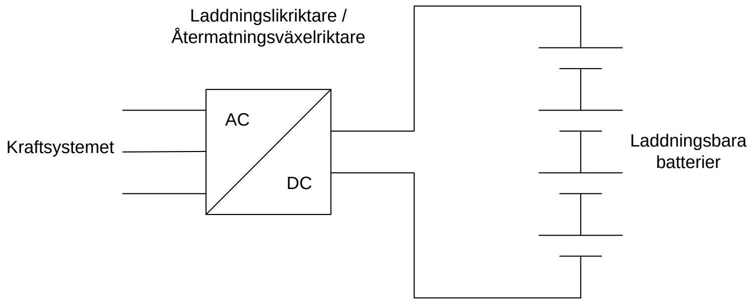
Den framtida elenergianvändningen, den framtida nederbörden och de därmed förknippade vattenkrafttillgångarna, värmekraftaggregatens framtida tillgänglighet samt den framtida utrikeshandeln påverkar alla det framtida spotpriset och därmed resultatet av utnyttjningen av anläggningarna för energilagring.

3 Teknikbeskrivningar

Nedan visas mycket översiktligt hur olika typer av energilager för kraftsystem kan byggas upp.

3.1 Energilagring i batterier

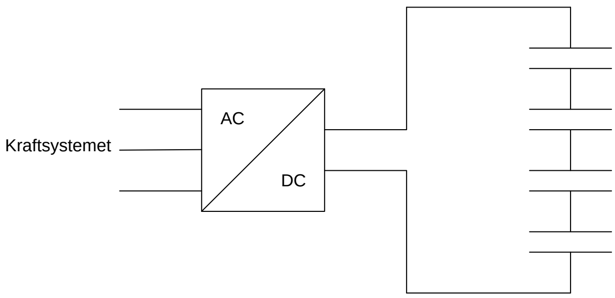
Figur 12 visar principen för ett energilager baserat på uppladdningsbara batterier. Vid perioder med produktionsöverskott i kraftsystemet fungerar strömriktaren som en likriktare och laddar batteriet. Vid perioder med behov av effekttillskott i kraftsystemet fungerar strömriktaren som en växelriktare och omvandlar den upplagrade energin i batteriet till elenergi som matas ut i kraftsystemet. I figuren visas laddningslikriktare och återmatningsväxelriktare som en enhet. Det är möjligt att bygga upp systemet med separat likriktare för batteriladdning och separat växelriktare för återmatning till kraftsystemet.



Figur 12: Princip för batteribaserat energilager

3.2 Energilagring i kraftkondensatorer

Figur 13 visar principen för ett energilager baserat på upp- och urladdning av kondensatorer. Vid perioder med produktionsöverskott i kraftsystemet fungerar strömriktaren som en likriktare och laddar kondensatorenheten. Vid perioder med behov av effekttillskott i kraftsystemet fungerar strömriktaren som en växelriktare och omvandlar den upplagrade energin i kondensatorenheten till elenergi som matas ut i kraftsystemet. I figuren visas laddningslikriktare och återmatningsväxelriktare som en enhet. Det är möjligt att bygga upp systemet med separat likriktare för laddning och separat växelriktare för återmatning till kraftsystemet.

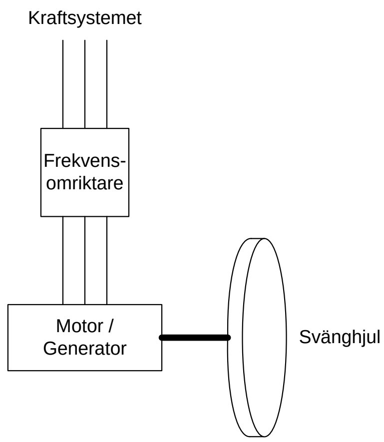


Figur 13: Princip för kondensatorbaserat energilager

Superkondensatorer har utvecklats på senare år med kapacitans upp mot 2000 Farad och mer, se referens [1]. Jämfört med laddningsbara batterier är dock energitätheten trots detta mindre.

3.3 Energilagring i svänghjul

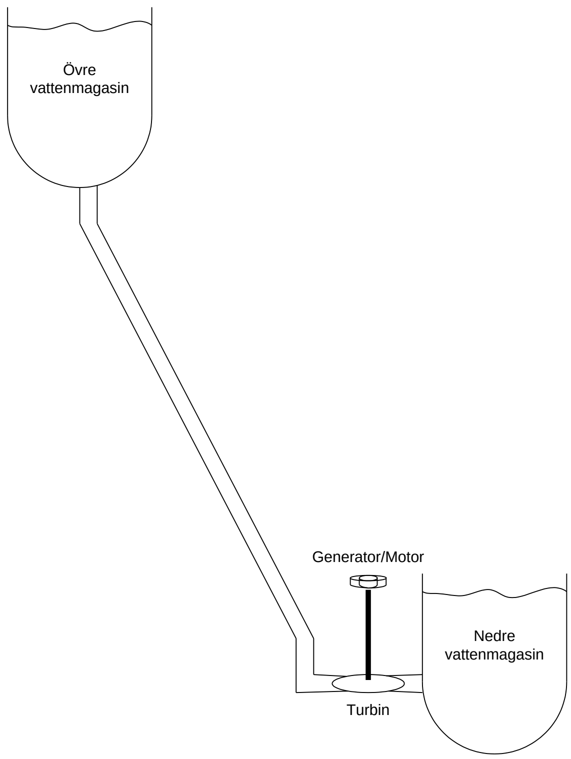
Figur 14 visar principen för ett energilager baserat svänghjul. Svänghjulet är kopplat till ett motor/generatoraggregat. Vid perioder med produktionsöverskott i kraftsystemet lagras energi i svänghjulet såsom rörelseenergi. Detta sker genom att öka rotationshastigheten hos det mekaniska svänghjulet. Vid perioder med behov av effekttillskott i kraftsystemet omvandlas den upplagrade energin i svänghjulet till elenergi som matas ut i kraftsystemet. Eftersom energiinnehållet i svänghjulet är beroende av rotationshastigheten måste även motor/generatoraggregatet kunna drivas med variabelt varvtal. Frekvensomriktare uppbyggda med modern transistorteknik är väl lämpade för att styra motorer/generatorer med variabelt varvtal. Varvtal upp mot 10 000 varv/minut kan vara realistiska.



Figur 14: Princip för energilagring i svänghjul

3.4 Energilagring i pumpkraftverk

Figur 15 visar principen för ett pumpkraftverk. Pumpkraftverket är i princip ett normalt vattenkraftverk med övre och nedre vattenmagasin som kan rymma en vattenmängd motsvarande den energimängd som man vill lagra. Vid upplagring av energi fungerar synkronmaskinen som motor och pumpar upp vatten till det övre magasinet. När den upplagrade energin skall återmatas till kraftsystemet fungerar synkronmaskinen som generator.

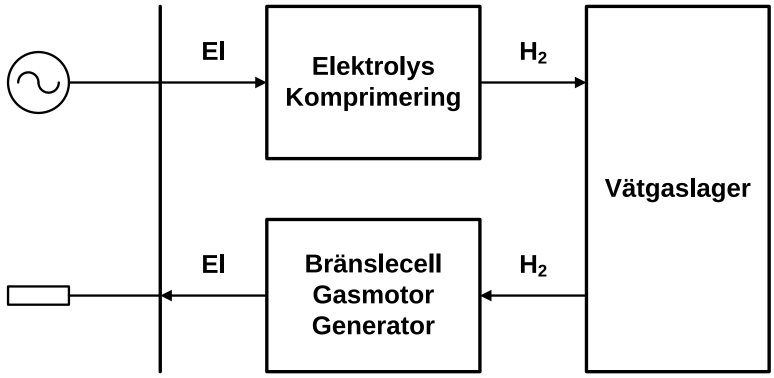


Figur 15: Översiktsbild av pumpkraftverk

Normalt byggs pumpkraftverk i terräng där övre och nedre magasin kan fås på naturligt vis, till exempel med sjöar på olika nivå. Dock skulle det vara möjligt att spränga ut det nedre magasinet under jord (sub-terra). Här kan man överväga att använda befintliga underjordsmagasin i nedlagda (utbrutna) gruvor. Tidigare byggdes flera pumpkraftverk med en pump och en turbin men numera bygger man gärna pumpkraftverk med en reversibel pump/turbin. Man får på så sätt bara en strömningsmaskin men med olika rotationsriktning vid pumpning och generering.

3.5 Energilagring genom vätgasgenerering

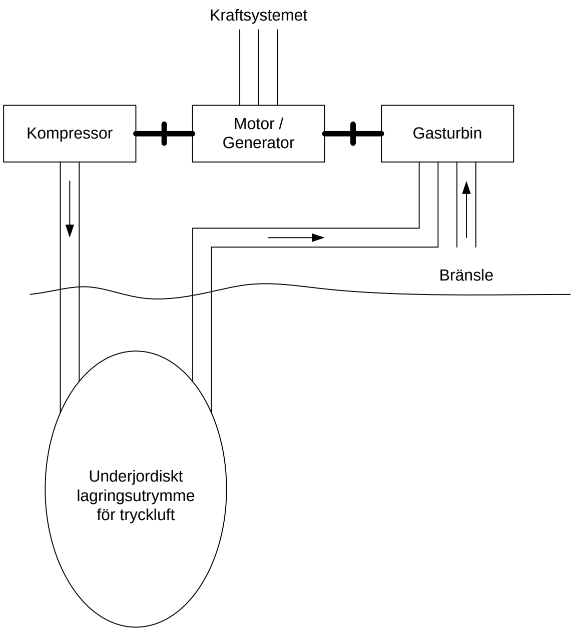
Figur 16 visar principen för energilagring genom vätgasgenerering. Energi lagras genom att generera vätgas till exempel genom elektrolys och att komprimera gasen. El produceras i en bränslecell eller gasmotor plus roterande generator.



Figur 16: Energilagring genom vätgasgenerering

3.6 Energilagring genom luftkomprimering

Figur 17 visar principen för energilagring med komprimerad luft. Vid perioder med produktionsöverskott i kraftsystemet drivs synkronmaskinen (motor/generatoraggregatet) som motor och driver en kompressor som pumpar luft till ett lagringsutrymme för tryckluft. Detta lagringsutrymme är normalt underjordiskt.



Figur 17: Principiell uppbyggnad av system för energilagring med tryckluft

Vid perioder med produktionsunderskott i kraftsystemet leds den komprimerade luften till en brännkammare där bränslet förbränns och den varma gasen driver turbin som i sin tur är ansluten till synkronmaskinen (motor/generatoraggregatet). En gasturbin driver normalt en egen kompressor för sitt eget driftbehov. I detta fall används den upplagrade tryckluften i stället för en kompressor. Därmed kan man nyttja bränslet till gasturbinen på ett effektivt sätt samtidigt som tryckluften som krävs av processen har genererats med billiga kraftslag vid perioder med produktionsöverskott.

4 Användningsområden

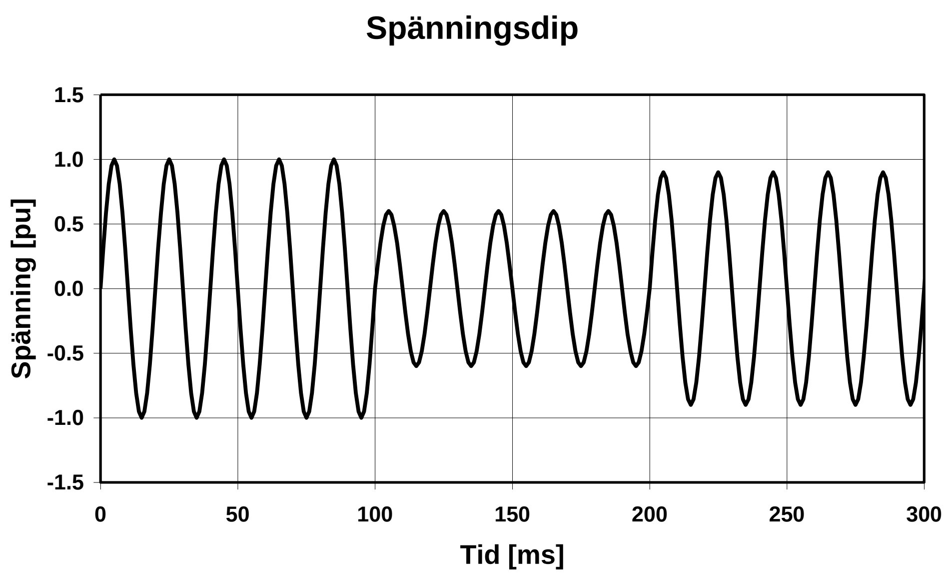
Energilagring kan påverka konkurrenskraften för intermittenta produktionstekniker och effektivisera driften av elförsörjningssystemet. I detta avsnitt inventeras tänkbara användningsområden för anläggningar för energilagring.

4.1 Förbättring av elkvalitet

Utöver avbrottsfrekvens och avbrottstid brukar man med elkvalitet mena:

- kraftsystemets förmåga att mata belastningsobjekten utan att störa eller skada dem vilket i stor utsträckning beror på spänningens kurvform
- belastningsobjektens förmåga att drivas utan att störa eller minska effektiviteten i kraftsystemet vilket i stor utsträckning beror på belastningsströmmens kurvform

Ett fenomen som brukar känneteckna elkvalitet är förekomsten av spänningsdippar, se Figur 18 nedan, som kan orsakas av shuntfel (kortslutningar och jordslutningar) på objekt i närheten av det belastningsobjekt som är av intresse.

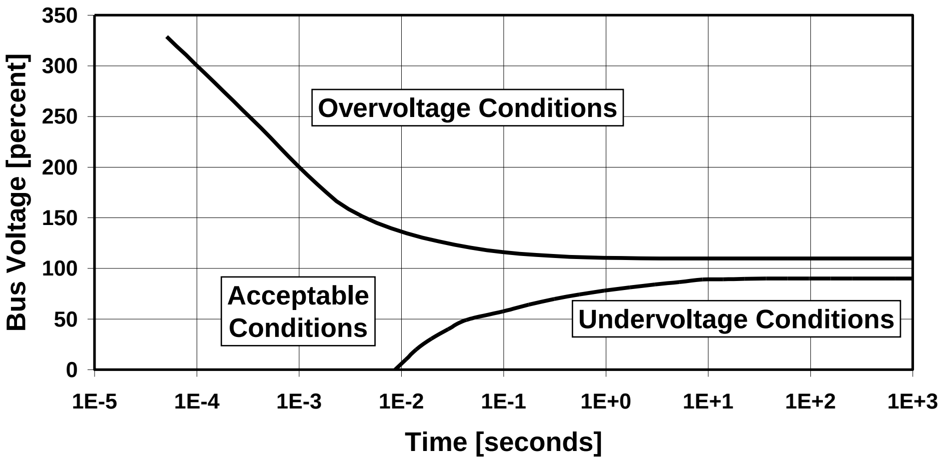


Figur 18: Spänningsdip

Övertoner och spänningsfluktuationer är andra fenomen som är förknippade med elkvalitet.

Computer Business Equipment Manufacturer Association (CBEMA) har publicerat en kurva, se Figur 19, som ursprungligen togs fram som vägledning för CBEMA-medlemmarnas arbete att konstruera kraftförsörjningen i datorer och annan elektronisk utrustning. Kurvan brukar även användas för att värdera (1) elkvalitén i kraftsystem och (2) risken för att datorer och annan elektronisk utrustning ska felfungera.

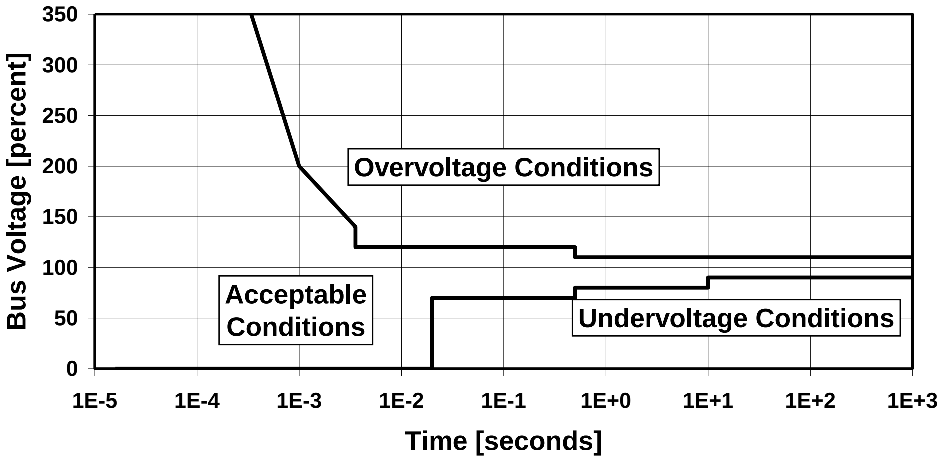
CBEMA kurvan
Efter: Arrilaga, Bollen & Watson (2000)



Figur 19: CBEMA kurvan

CBEMA heter numera Information Technology Industry Council (ITIC) och kurvan i Figur 20 har tagits fram för att ersätta CBEMA kurvan.

ITIC kurvan
Efter: Arrilaga, Bollen & Watson (2000)



Figur 20: ITIC kurvan

En anläggning för energilagring kan förbättra el-kvalitén på följande sätt:

- avbrottsfri elförsörjning av kritiska belastningsobjekt med hjälp av Uninterruptible Power Supply system (UPS system)
- förbättring av spänningshållningen med hjälp av ett energilager och snabb reglering av den utmatade strömmen

Aktiveringstiden för anläggningar för förbättring av el-kvalitén bör vara kortare än en period av fundamentalfrekvensen och medelutnyttjningstiden några minuter per år.

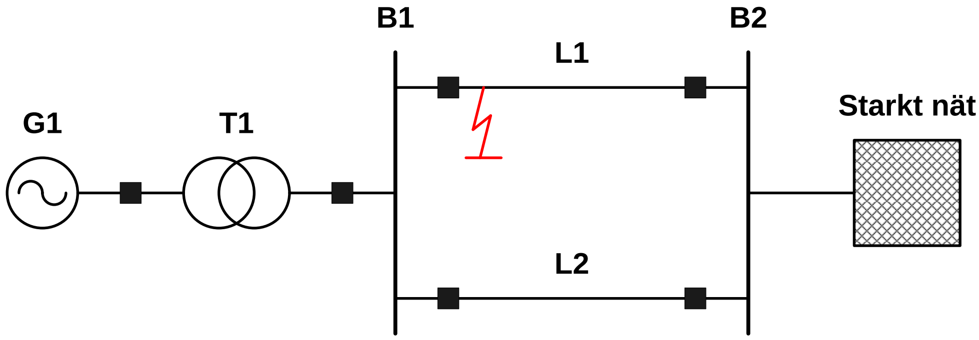
Den ekonomiska nyttan beror i stor utsträckning på tillämpningen. Elförsörjning av säkerhetsrelaterade objekt i kärnkraftstationer måste bara finnas. Tillverkare av halvledarkomponenter har valt plats för lokalisering bland annat efter granskning av el-kvalitén på tänkbara lokaliseringsorter.

4.2 Förbättring av den transienta stabiliteten

Vid jordslutningar och framför allt kortslutningar på elnäten sjunker spänningen och utmatningen av elenergi från någon eller några generatorer kan minska. Om så sker rubbas balansen mellan det accelererande mekaniska momentet och det retarderande elektriska momentet hos vissa generatorer. Så länge det primära störningsfelet inte hunnit kopplas bort accelereras turbingeneratoraggregaten nära felstället snabbt på grund av att nätspänningen är låg och den från aggregaten retarderande utmatade elektriska effekten är obetydlig. Den accelererande mekaniska effekten är ungefär lika stor som den var innan felet inträffade. Normalt kopplas den feldrabbade anläggningsdelen bort efter en kortare tid än 100 millisekunder. När det primära störningsfelet kopplas bort stiger nätspänningen, vilket leder till att den retarderande utmatade elektriska effekten ökar. På grund av att transmissionsnätet är försvagat och den retarderande utmatade elektriska effekten blir lika med den accelererande mekaniska effekten när generatorns rotorvinkel når ett kritiskt värde börjar rotationshastigheten minska och om transmissionsnätet är tillräckligt starkt kommer rotorvinkeln att börja minska. Om transmissionsnätet är kraftigt försvagat finns det risk att aggregatet faller ur fas.

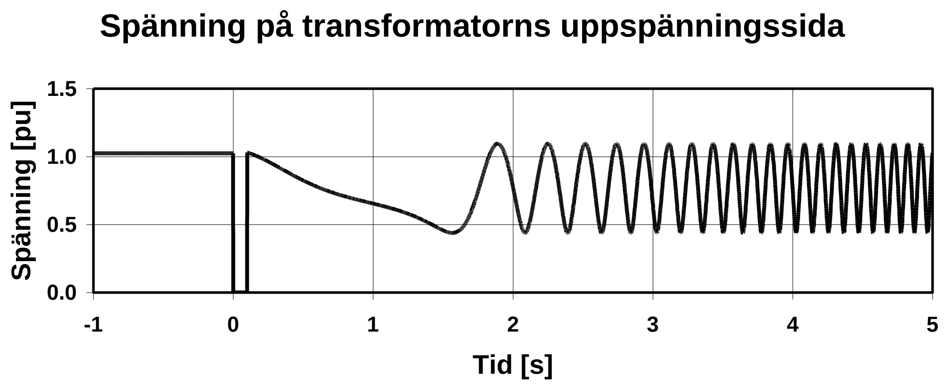
4.2.1 Åskådningsexempel

För att illustrera ovanstående beskrivning studeras det system som visas i Figur 21. I detta åskådningsexempel antas att generatorn har en skenbar effekt om 1 500 MVA.



Figur 21: Enlinjeschema för åskådningsexempel på transient stabilitet

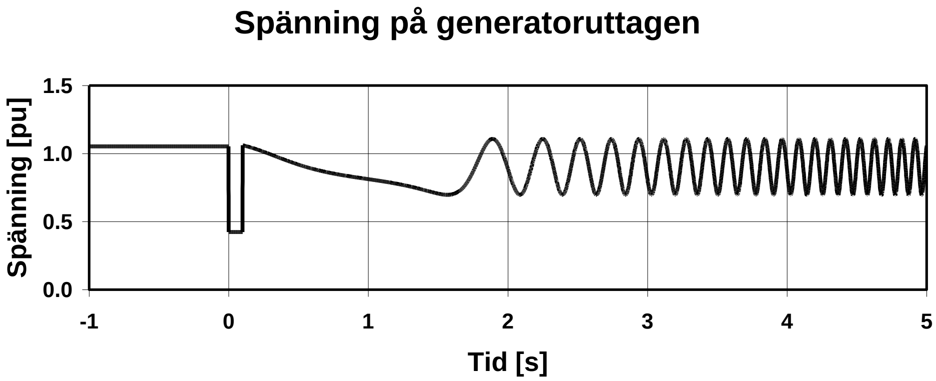
Vi antar att ledning L1 drabbas av en trepolig kortslutning omedelbart utanför ledningsbrytaren i stationen med samlingsskena B1. Spänningen på samlingsskena B1 kommer då att sjunka till ett värde mycket nära noll, se Figur 22.



Figur 22: Spänning på transformatorns uppspänningssida

Under feltiden kommer spänningen på samlingsskena B1 att anta ett värde nära noll. När kortslutningen kopplats bort stiger spänningen på samlingsskena B1 till ett värde i närheten av den normala driftspänningen.

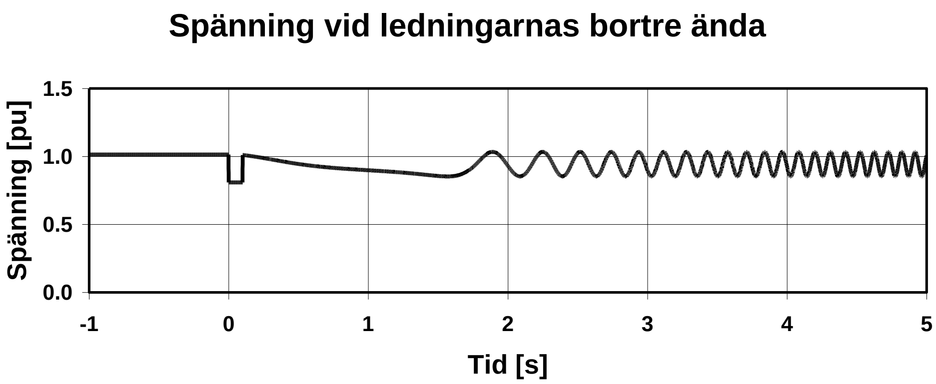
Även spänningen på generatorns fasuttag sjunker under feltiden, se Figur 23.



Figur 23: Spänning på generatorns fasuttag

Under feltiden sjunker spänningen på generatorns fasuttag till ett värde som bestäms av transformatorns kortslutningsreaktans och generatorns subtransienta reaktans.

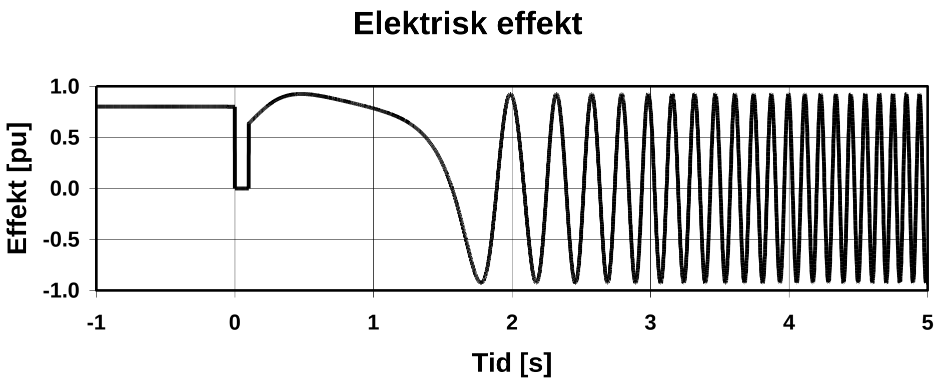
Även spänningen på samlingsskena B2 vid bortre ändan av de båda ledningarna L1 och L2 sjunker under feltiden som framgår av Figur 24.



Figur 24: Spänning på samlingsskenan vid bortre ändan av ledningarna

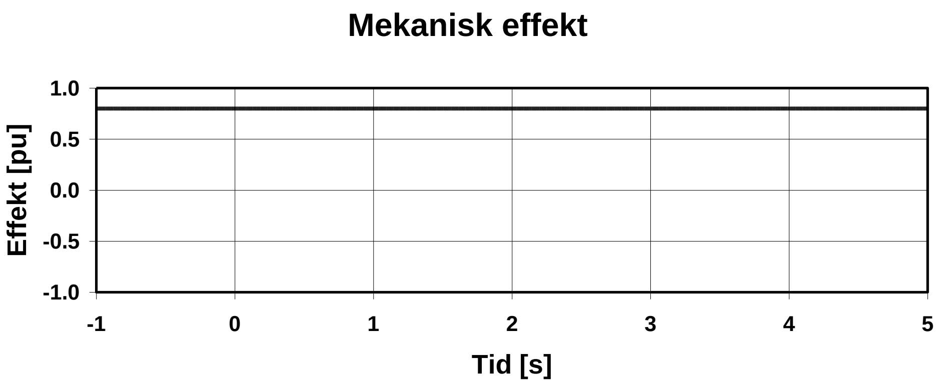
Under feltiden sjunker spänningen på samlingsskena B2 till ett värde som bestäms av nätets kortslutningsreaktans och ledningarnas reaktans.

Spänningssänkningen på samlingsskena B1 gör att den utmatade aktiva effekten från generator G1 till nätet sjunker till ett värde nära noll under feltiden, se Figur 25 medan den mekaniska effekten till aggregatets roterande delar är nästan konstant som framgår av Figur 26.



Figur 25: Elektrisk effekt från generatorn

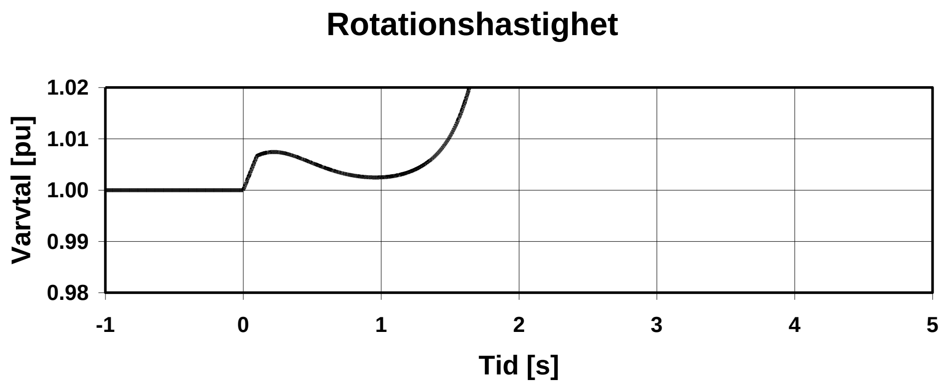
Innan felet inträffar är den elektriska effekten lika med den mekaniska effekten om vi försummar alla förluster.



Figur 26: Mekanisk effekt till aggregatets roterande delar

Här antar vi att den mekaniska effekten till aggregatets roterande delar är konstant, vilket är ett rimligt antagande.

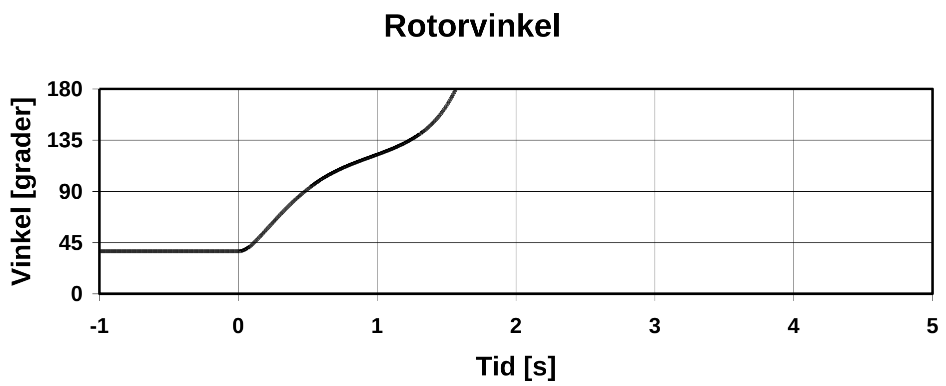
Skillnaden mellan mekanisk effekt och elektrisk effekt brukar kallas accelererande effekt eftersom den ökar turbingenerators rotationsvarvtal, som framgår av Figur 27.



Figur 27: Turbin- generatoraggregatets rotationshastighet

Om inte varvtalsstegringen hejdas i tid faller aggregatet ur fas och kopplas i allmänhet bort från det övriga nätet.

Figur 28 visar vinkeln mellan generatorns rotor och det starka nätet och Figur 22 till och med Figur 28 beskriver alla ett fall av transient instabilitet.

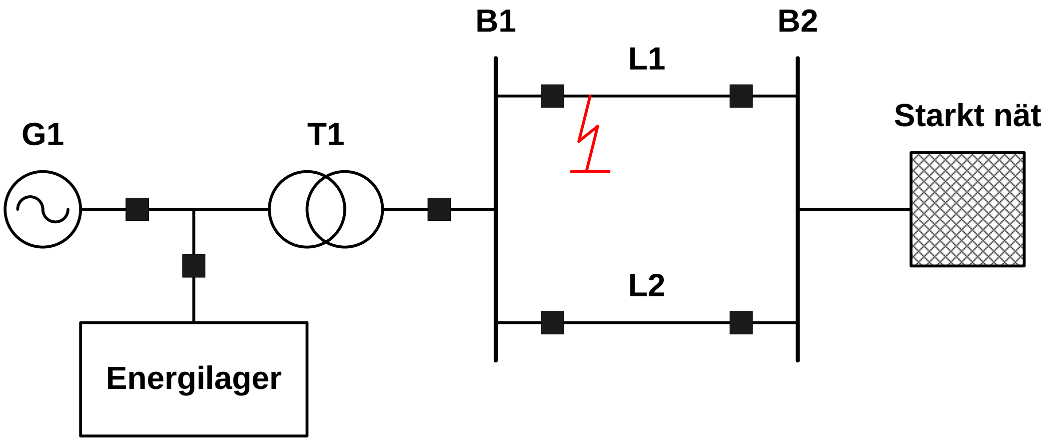


Figur 28: Vinkel mellan generatorns rotor och det starka nätet

4.2.2 Förbättring av den transienta stabiliteten

En anläggning för energilagring, som kan öka det retarderande elektriska momentet under och efter feltiden, skulle kunna bidra till att minska risken för transient instabilitet. Detta i sin tur skulle kunna bidra till ökad överföringsförmåga hos det befintliga elförsörjningssystemet och eventuellt även senareläggning av planerade förstärkningar av överföringsnätet.

Nedan visas hur ett energilager, se Figur 29, kan utnyttjas för att förhindra transient instabilitet hos det åskådningsexempel som beskrivs i avsnitt 4.2.1.

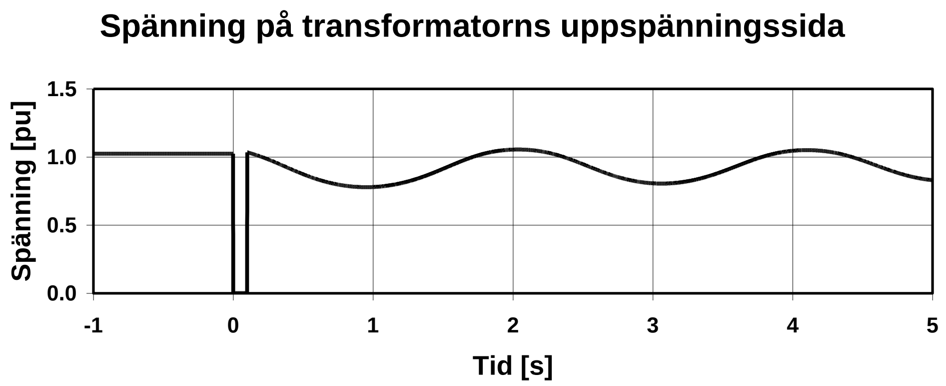


Figur 29: Enkelt kraftsystem med energilager

Observera att energilagret är anslutet till nedspänningssidan av aggregat-transformatorn och inte till samlingsskenan B1. Om energilagret hade varit anslutet till skena B1 skulle det inte vara möjligt att ladda energilagret under feltiden på grund av att spänningen på skena B1 då är nära noll. På nedspän-ningssidan sjunker spänningen men det finns viss spänning, se Figur 23 som gör det möjligt att ladda energilagret.

Vid konstruktionen av det energilager som visas i Figur 29 måste man beakta att kortslutningseffekten i anslutningspunkten är mycket hög. Särskilda åt-gärder kan behöva vidtas för att alla delar i anläggningen för energilagring inte ska bli utsatt för dessa höga felströmmar.

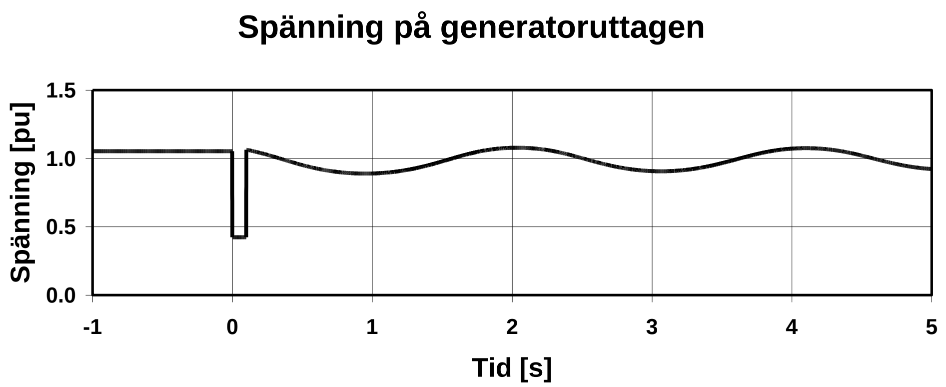
Det antas att ledning L1 drabbas av en trepolig kortslutning omedelbart utan-för ledningsbrytaren i stationen med samlingsskena B1. Spänningen på sam-lingsskena B1 kommer då att sjunka till ett värde mycket nära noll, se Figur 30.



Figur 30: Spänning på transformatorns uppspänningssida

När kortslutningen kopplats bort stiger spänningen på samlingsskena B1 till ett värde i närheten av den normala driftspänningen.

Även spänningen på generatorns fasuttag sjunker under feltiden, se Figur 31



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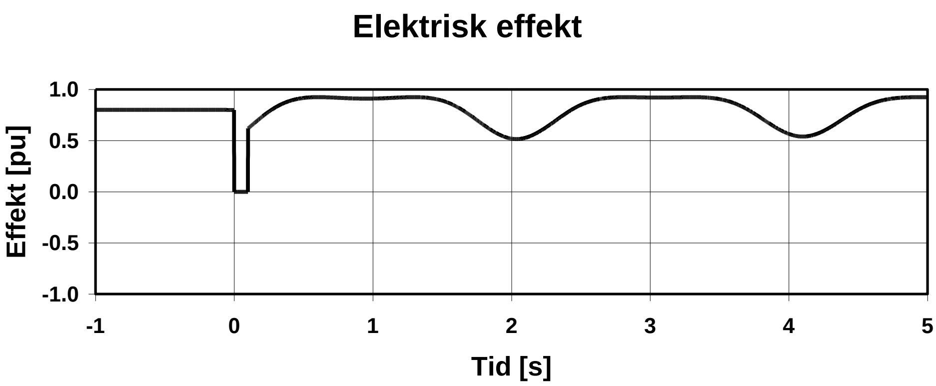
Figur 31: Spänning på generatorns fasuttag

Under feltiden sjunker spänningen på generatorns fasuttag till ett värde som bestäms av transformatorns kortslutningsreaktans, generatorns subtransienta reaktans och effekten till energilagret.

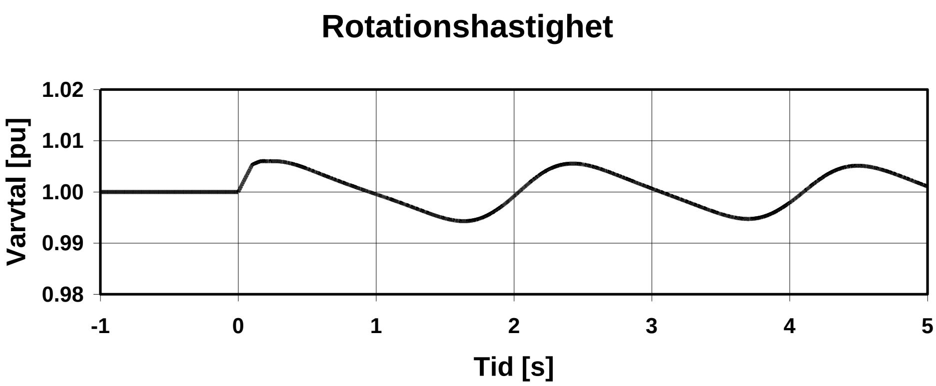
Spänningssänkningen på samlingsskena B1 gör att den utmatade aktiva effekten från generator G1 till nätet sjunker till noll under feltiden, se Figur 32.



Figur 32: Elektrisk effekt från generatorn

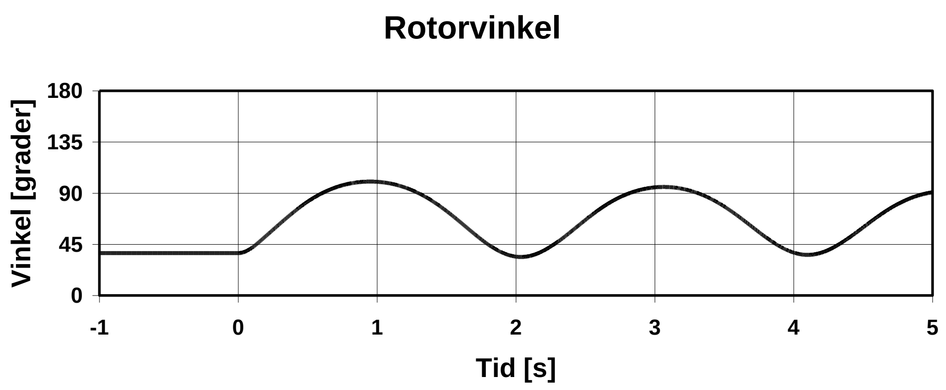
Innan felet inträffar är den elektriska effekten lika med den mekaniska effekten om vi försummar alla förluster. Här antar vi att den mekaniska effekten till aggregatets roterande delar är konstant, vilket är ett rimligt antagande.

Figur 33 visar turbin- generatorns rotationsvarvtal.



Figur 33: Turbin- generatoraggregatets rotationshastighet

Figur 34 visar vinkeln mellan generatorns rotor och det starka nätet.



Figur 34: Vinkel mellan generatorns rotor och det starka nätet

Energilagret förmår att förhindra transient instabilitet men dämpningen av de elektromekaniska pendlingarna är inte tillfredställande.

Figur 35 visar den effekt som flyter till energilagret.

Figur 35: Effektflöde till energilagret

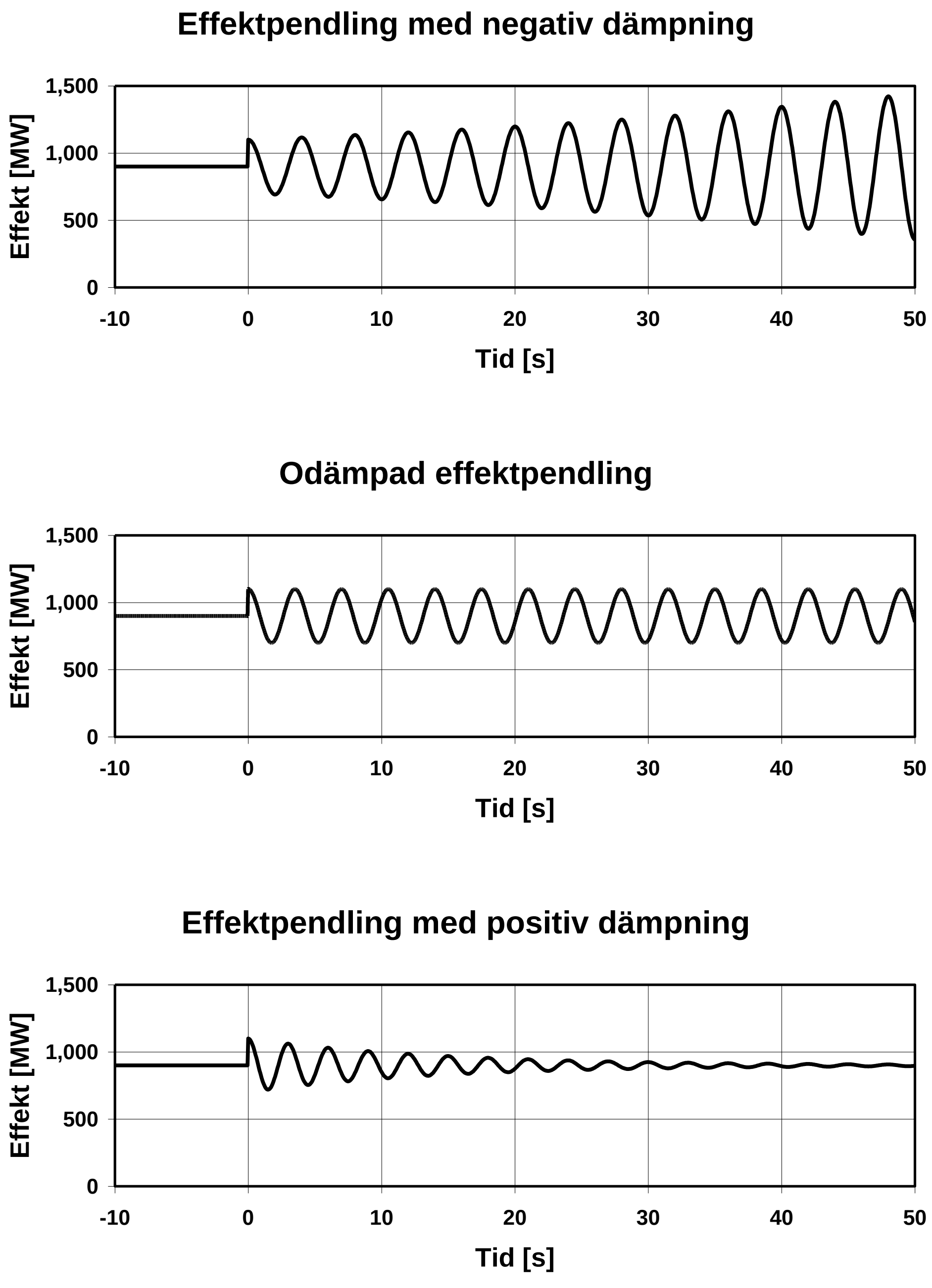
För att undvika transient instabilitet har energilagret i detta exempel laddats med en högsta effekt om cirka 250 MW och lagrat 0,007 MWh. Här antas att den under feltiden upplagrade energin återmatas vid ett senare tillfälle så att anläggningen för energilagring är redo att lagra energi vid nästa fel på det yttre nätet. I åskådningsexemplet ovan antas att energi lagrades endast under feltiden. Man kunde dessutom ha lagrat energi så länge aggregatet accelererades. Detta är det normala förfarandet när man använder bromsmotstånd för att förbättra den transienta stabiliteten. För att ett bromsmotstånd ska kunna aktiveras under feltiden måste det vara försett med ett snabbare kopplingsorgan än en mekanisk elkopplare (effektbrytare).

Aktiveringstiden måste vara kort och bör inte vara längre än cirka 100 millisekunder och insatstiden upp emot 1 sekund. Storleken av energilagret behöver inte vara större än summan av den installerade aktiva effekten som riskerar att falla ur fas vid ett primärt störningsfel men bör inte vara mindre än cirka 20 % av den installerade effekten. De största aggregaten i det synkrona Nordel-systemet har för närvarande en installerad effekt om cirka 1 200 MW. Denna kommer att öka till cirka 1 450 respektive 1 600 MW efter effekthöjningarna i befintliga värmekraftaggregat i Sverige och idrifttagning av ett nytt värmekraftaggregat i Finland. Ett energilager med en effekt om cirka 300 MW och en lagringskapacitet om 0,01 MWh har förutsättningar att påtagligt reducera risken för transient instabilitet i åskådningsexemplet. Observera att det måste vara möjligt att absorbera elektrisk effekt även om spänningen på överföringsnätet skulle vara så låg som cirka 50 % av den normala driftspänningen.

4.3 Dämpning av elektromekaniska pendlingar

De elektromekaniska pendlingar mellan generatorer och grupper av generatorer, som uppkommer i samband med störningar i elförsörjningssystemet måste dämpas ut. Störningarna kan vara kortslutningar och jordslutningar eller bortkoppling av ledningar och transformatorer utan föregående fel. Om effektpendlingarna inte dämpas ut utan fortsätter att växa kommer generatorer så småningom att falla ur fas och kraftsystemet kommer att drabbats av dynamisk instabilitet. Det finns även ett behov att dämpa ut de elektromekaniska pendlingar som kan uppkomma till synes utan anledning (så kallade självalstrade pendlingar).

Figur 36 visar exempel på effektpendlingar med olika dämpning. Den översta kurvan visar en effektpendling med negativ dämpning medan den mellersta kurvan visar en effektpendling utan någon dämpning. Den nedersta kurva visar en effektpendling med positiv dämpning. Vid planeringen av Nordel-systemet har man tidvis använt kriteriet att en effektpendling skall minska till hälften på 10 sekunder.



Figur 36: Effektpendlingar med olika dämpning

Observera att terminologin varierar och ekvation (1) visar ett sätt att beskriva effektpendlingar i elkraftsystem.

$$P(t) = P_{\max} e^{-d \cdot t} \cos(\omega t + \delta) \qquad \textbf{(1)}$$

Effektpendlingar i elkraftsystem analyseras tidvis med hjälp av egenvärdes-analys av en linjäriserad modell och effektpendlingarna beskrivs av det dominerande paret av egenvärden till den linjäriserade modellen $\lambda_i = \sigma_i \pm j\omega_i$, se ekvation (2) nedan.

$$P(t) = P_{\max} e^{\sigma_i \cdot t} \cos(\omega_i t + \phi) \tag{2}$$

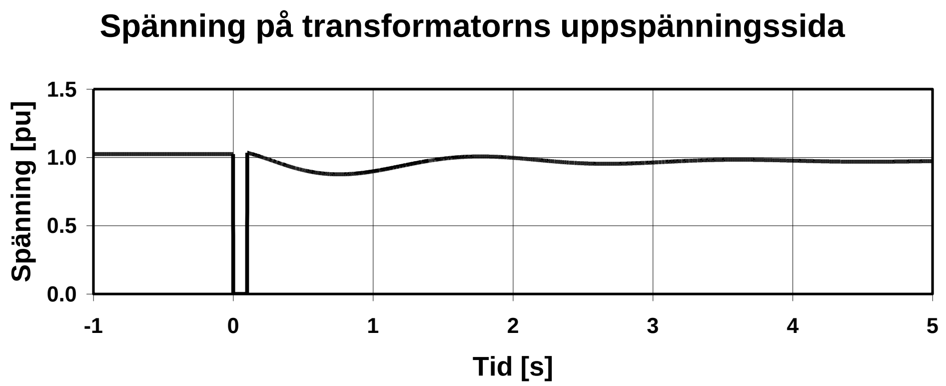
Den enda principiella skillnaden mellan ekvation (1) och (2) är tecknet på den term som anger dämpningen d respektive σ_i. I ekvation (1) ger ett positivt värde på parametern d positiv dämpning, det vill säga pendlingar med avtagande amplitud eller positiv dämpning enligt gängse språkbruk i elkraftsammanhang. I ekvation (2) ger ett negativt värde på parametern σ_i pendlingar med avtagande amplitud. I Figur 36 gäller att: $d = -0.02$ (översta kurvan), $d = 0.00$ (mellersta kurvan) och $d = 0.07$ (nedersta kurvan), vilket motsvarar $\sigma_i = 0.02$ (översta kurvan), $\sigma_i = 0.00$ (mellersta kurvan) och $\sigma_i = -0.07$ (nedersta kurvan). Med $d = 0.07$ minskar storleken på effektpendlingarna till hälften på 10 sekunder.

Ovan konstaterades att ett energilager som styrs på lämpligt sätt kan förhindra transient instabilitet. I åskådningsexemplet, se avsnitt 4.2.2, blev dämpningen av de elektromekaniska pendlingarna inte tillräcklig. Genom att komplettera styrutrustningen för energilagret i Figur 29 med en dämpterm kan dämpningen av de elektromekaniska pendlingarna förbättras. Dämptermen bör ge en effektinmatning till energilagret som är proportionell mot rotationshastighetens avvikelse från medelvärdet av rotationshastigheten hos övriga aggregat. Med rotationshastighet menas här kvoten mellan aktuellt varvtal och märkvarvtal. Nedan illustreras hur energilagret kan utnyttjas för att utöver att förhindra transient instabilitet även förbättra dämpningen av elektromekaniska pendlingar.

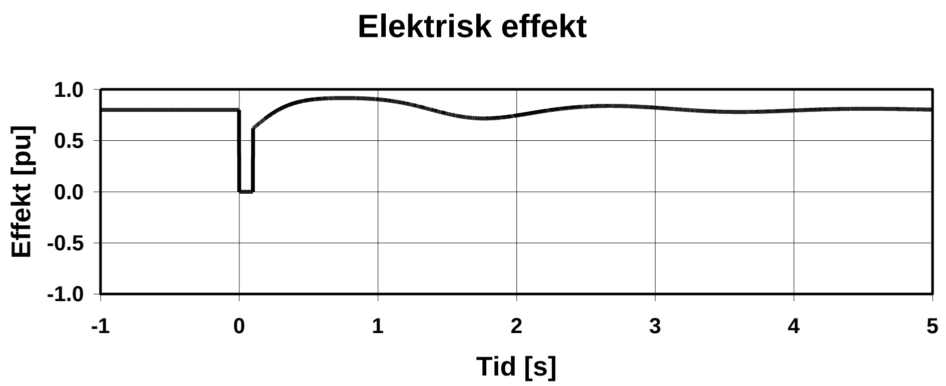
Det antas att ledning L1 drabbas av en trepolig kortslutning omedelbart utanför ledningsbrytaren i stationen med samlingsskena B1. Spänningen på samlingsskena B1 kommer då att sjunka till ett värde mycket nära noll, se Figur 37. När kortslutningen kopplats bort stiger spänningen på samlingsskena B1.

Spänningssänkningen på samlingsskena B1 gör att den utmatade aktiva effekten från generator G1 till nätet sjunker till noll under feltiden, se Figur 38.

Innan felet inträffar är den elektriska effekten lika med den mekaniska effekten om vi försummar alla förluster. Här antar vi att den mekaniska effekten till aggregatets roterande delar är konstant, vilket är ett rimligt antagande.

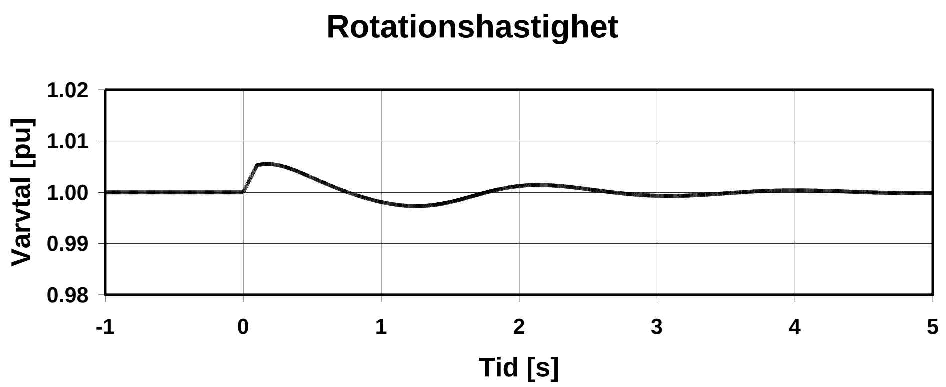


Figur 37: Spänning på transformatorns uppspänningssida



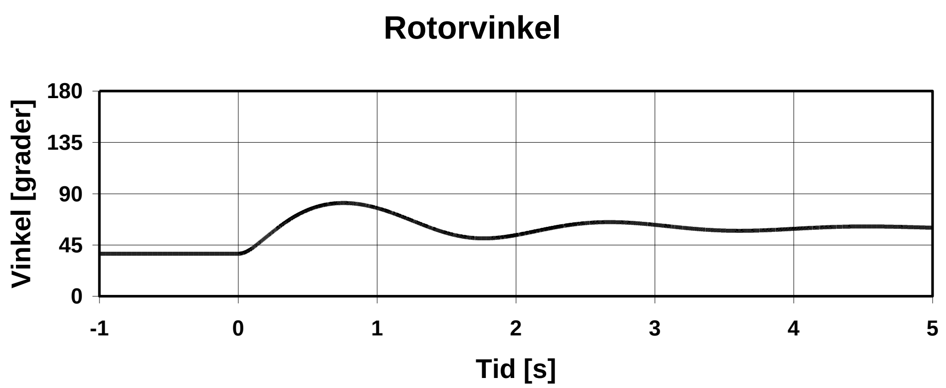
Figur 38: Elektrisk effekt från generatorn

Figur 39 visar turbin- generatorns rotationsvarvtal.



Figur 39: Turbin- generatoraggregatets rotationshastighet

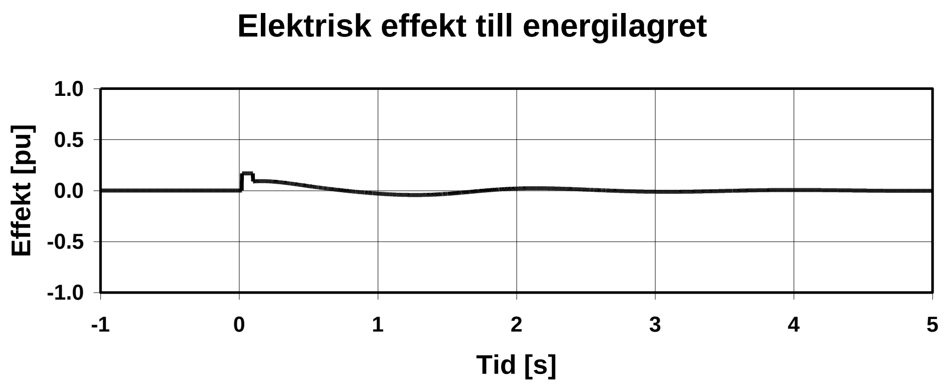
Figur 40 visar vinkeln mellan generatorns rotor och det starka nätet.



Figur 40: Vinkel mellan generatorns rotor och det starka nätet

Energilagret förmår att förhindra transient instabilitet och att öka dämpningen av de elektromekaniska pendlingarna.

Figur 41 visar den effekt som flyter till energilagret.



Figur 41: Effektflöde till energilagret

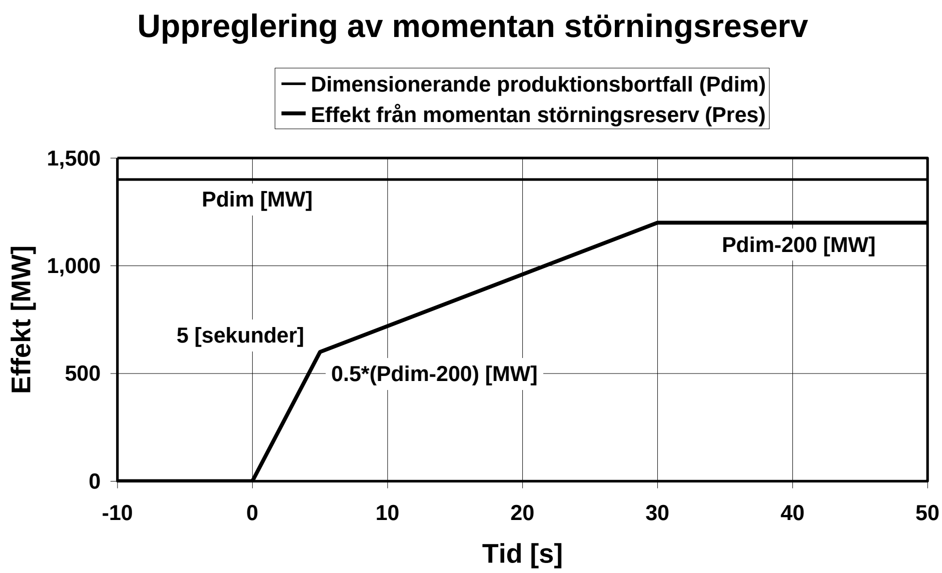
För att förbättra dämpningen var den maximala inmatningen till energilagret cirka 140 MW medan den maximala effektutmatningen var 65 MW. Skillnaden mellan den maximalt och den minimalt upplagrade energin var 0,015 MWh.

För att dämpa effektpendlingar gäller det att åstadkomma en periodiskt varierande eleffekt med medelvärdet noll, det vill säga omväxlande effektinmatning och effektuttagning, och en periodtid mellan 0,5 och 5 sekunder. Sådana energilager kan behöva installeras på ett fåtal perifera ställen i Nordelsystemet och effekten ska styras så att den varierar i takt med variationerna i vinkelfrekvens hos generatorerna i de aktuella områdena. För en grupp av generatorer med en sammanlagd skenbar effekt om 1 000 MVA behövs en anläggning med en effekt om 100 MW och en lagringskapacitet om 0,01 MWh. Observera att det måste vara möjligt att effektinmatningen och effektuttagningen kan ske även om spänningen på överföringsnätet skulle variera med ett tiotal procent av den normala driftspänningen.

4.4 Momentan aktiv störningsreserv

Vid bortfall av något turbingeneratoraggregat rubbas balansen mellan summa mekaniskt moment å ena sidan och summa elektriskt moment å andra sidan. Under förutsättning att samtliga kvarvarande generatorer i det växelströmsmässigt samkörande systemet förblir i synkronism och uppkomna pendlingar dämpas ut kommer alla aggregat att retarderas och medelfrekvensen i systemet sjunker. För närvarande gäller kravet att nätfrekvensen efter ett stort produktionsbortfall i det synkrona Nordel-systemet inte ska sjunka under 49,0 Hz. Efter en tid kommer den momentana aktiva produktionsreserven, och frekvensreglerreserven, om den inte redan är fullt utnyttjad, att börja öka sin uteffekt och frekvensfallet kommer att hejdas. Det finns ett krav att nätfrekvensen 30 sekunder efter ett stort produktionsbortfall inte ska vara lägre än 49,5 Hz. Praktiskt innebär detta att den aktiva effektbalansen måste vara återupprättad inom cirka 5 sekunder. Den momentana aktiva störningsreserven i det växelströmsmässigt samkörande Nordel-systemet ska vara större än $P_{\mathrm{dim}} - 200$ MW där P_{dim} är storleken på det dimensionerande produktionsbortfallet, normalt det största aggregatet i systemet. När nätfrekvensen sjunker under 50 Hz kommer elförbrukningen i hela systemet att sjunka under det värde som gällde vid 50 Hz. Belastningsobjektens frekvensberoende hjälper till att återupprätta den aktiva effektbalansen och den minskade effektförbrukningen vid 49,5 Hz anses vara 200 MW i det synkrona Nordel-systemet.

Figur 42 visar i grafisk form kraven på uppregleringen av den totala aktiva störningsreserven i det synkrona Nordel-systemet för det fall att det dimensionerande produktionsbortfallet är lika med 1 400 MW. Uthålligheten måste vara minst 15 minuter, vilket leder till kravet att lagringskapaciteten måste vara minst 250 till 350 MWh för hela Nordel-systemet.



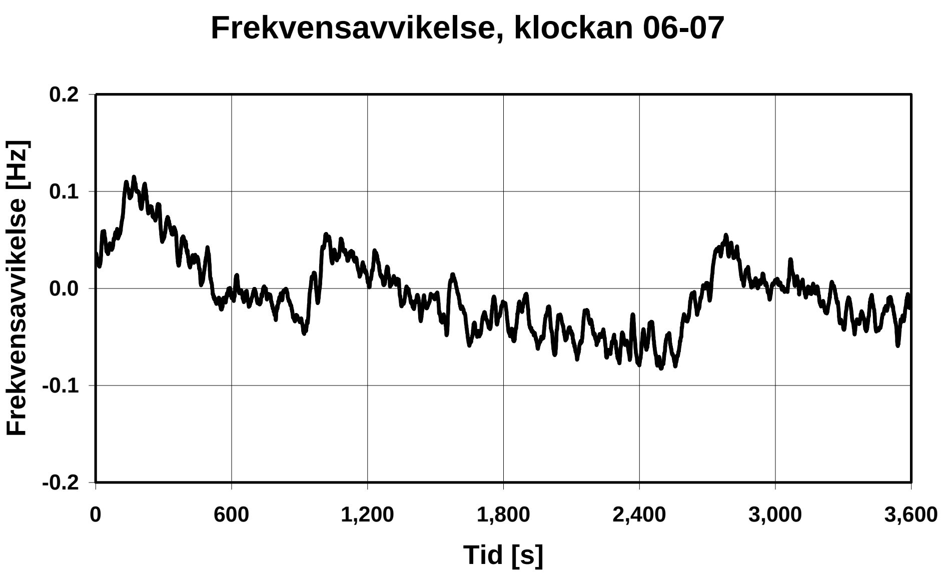
Figur 42: Uppreglering av den momentana aktiva störningsreserven

Kravet på storleken av den momentana aktiva störningsreserven fördelas mellan områdena i Nordel-systemet i proportion till det dimensionerande produktionsbortfallet i respektive delsystem. Detta innebär att Sverige, för närvarande, ska hålla en momentan aktiv störningsreserv som uppgår till cirka 1/3 av den totala reserven, vilket innebär ett värde i området mellan 300 och 400 MW

4.5 Frekvensreglering

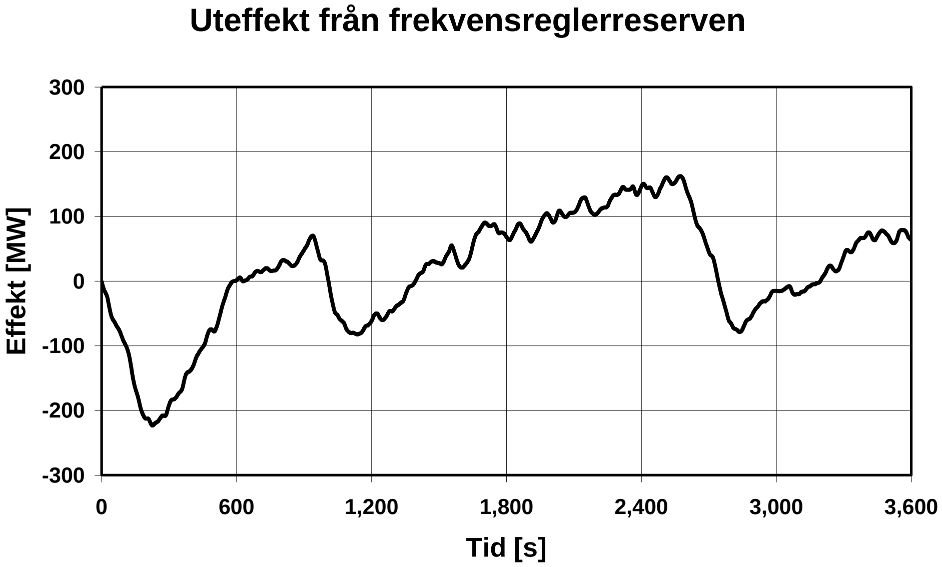
För att möta tillfälliga belastningsvariationer och effektobalanser, som uppkommer i samband med normal start och stopp av aggregat, ska det i Nordel-systemet finnas en frekvensreglerreserv. Denna reserv ska ha en storlek om 600 MW och den ska ingripa med en reglerstyrka om 6 000 MW/Hz. Kravet att hålla frekvensreglerreserv och reglerstyrka fördelas mellan områdena i det synkrona Nordel-systemet i proportion till den årliga elenergiförbrukningen inom området. Kravet och reglerna för fördelning leder till att man i Sverige ska hålla en frekvensreglerreserv om närmare 250 MW och en reglerstyrka om närmare 2 500 MW/Hz. Kraven inom Nordel anger att effekten från frekvensreglerreserven ska vara proportionell mot frekvensens medelvärde under 2 till 3 minuter. Detta innebär att det slutna reglersystemet kan ha en dominerande tidskonstant om cirka en minut. Frekvensvariationer i det synkrona Nordel-systemet håller sig normalt inom ±0,1 Hz och tidsavvikelsen inom ±30 sekunder. Kostnaden för att hålla frekvensreglerreserven i Sverige kan uppskattas till mellan 150 och 200 MSEK/år.

För att illustrera behovet av frekvensreglering betraktas tre timmar från torsdagen den 15 december 2005. Timmarna mellan kl. 06 och 07 (morgonpålastningen), mellan kl. 10 och 11 (jämn belastning) samt mellan kl. 22 och 23 (kvällsavlastningen) analyseras. Figur 43 visar frekvensavvikelsen under morgonpålastningen den 15 december 2005.



Figur 43: Frekvensavvikelsen under morgonpålastningen

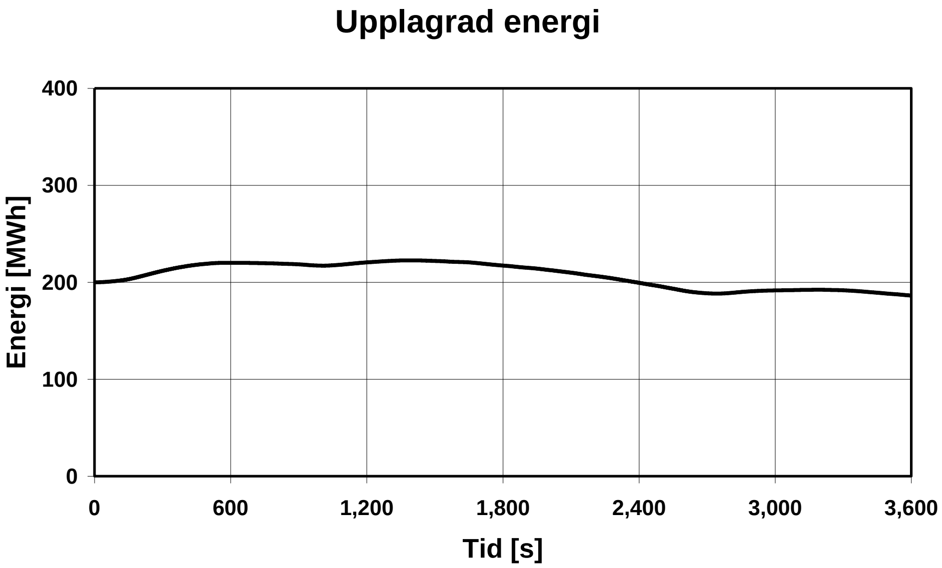
Figur 44 visar effektvariationerna från frekvensreglerreserven när reglerstyrkan är 2 500 MW/Hz.



Figur 44: Effektvariationer från frekvensreglerreserven

Den lägsta och högsta effektutmatningen är lika med -223 respektive 162 MW.

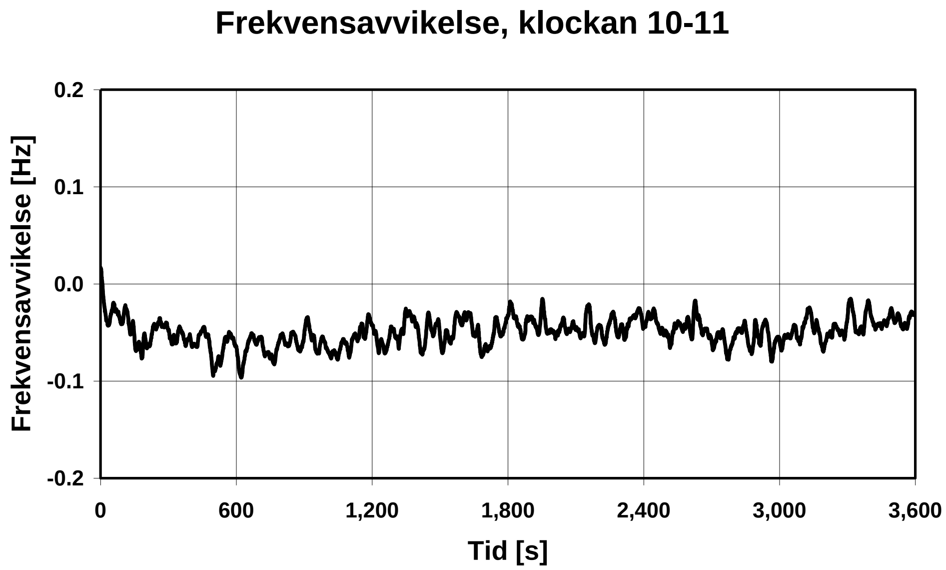
Figur 45 visar ändringen av den upplagrade energin under timmen. Begynnelsevärdet för den upplagrade energin är godtyckligt valt.



Figur 45: Upplagrad energi

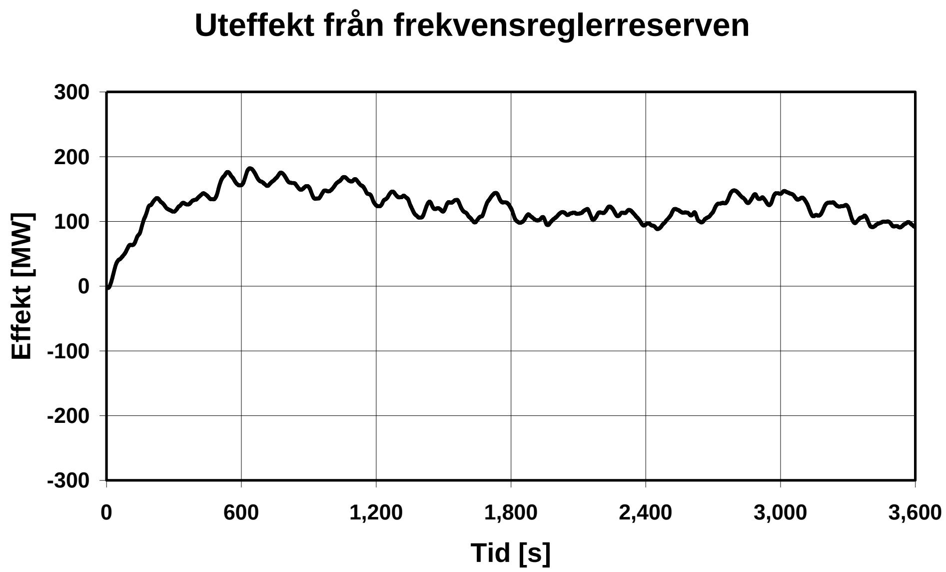
Den lägsta och högsta upplagrade energin är lika med 187 respektive 223 MWh och skillnaden är lika med 37 MWh

Figur 46 visar frekvensavvikelsen under jämn belastning den 15 december 2005.



Figur 46: Frekvensavvikelsen under jämn belastning

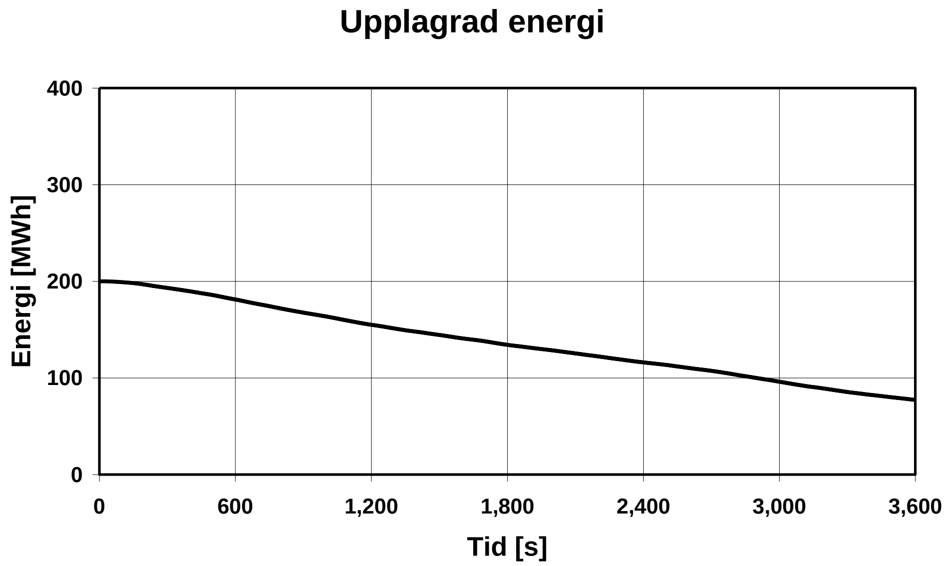
Vi noterar att frekvensen ligger stadigt över det lägsta tillåtna värdet 49,9 Hz men under den nominella frekvensen 50,0 Hz. Figur 47 visar effektutmatningen från frekvensreglerreserven under samma antagande som ovan.



Figur 47: Uteffekt från frekvensreglerreserven

Den lägsta och högsta effektutmatningen är lika med -3 respektive 182 MW.

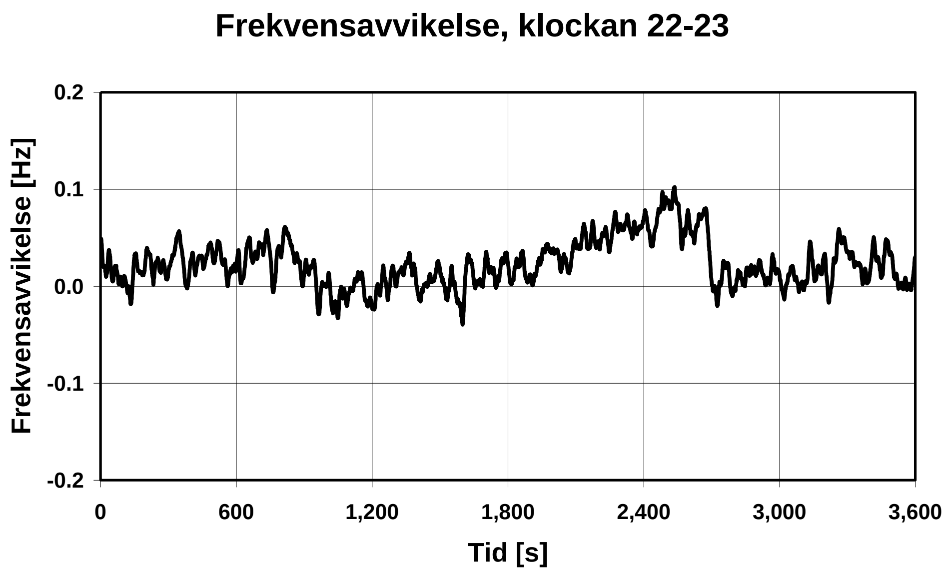
Figur 48 visar den upplagrade energin under timmen.



Figur 48: Upplagrad energi

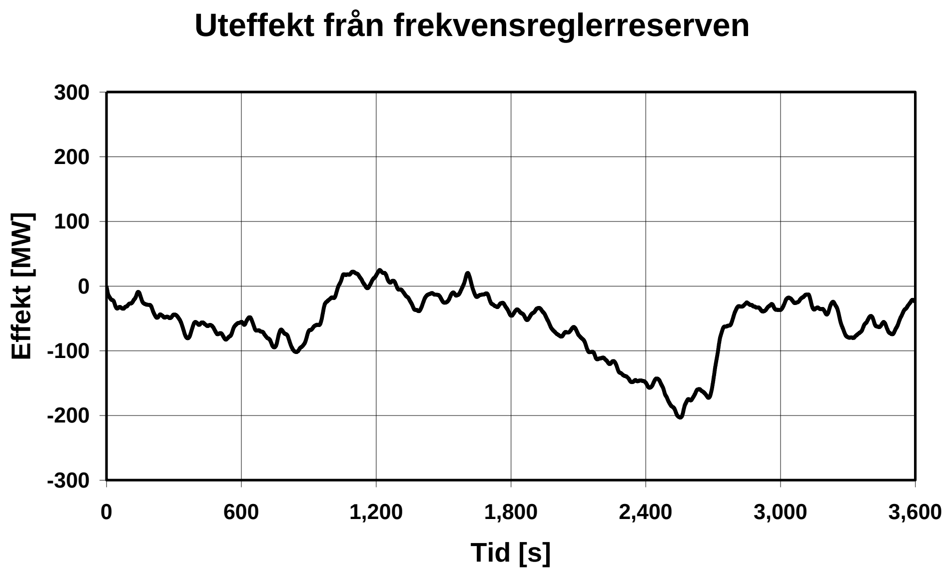
Den lägsta och högsta upplagrade energin är lika med 77 respektive 200 MWh och skillnaden är lika med 123 MWh

Figur 49 visar frekvensavvikelsen under kvällsavlastningen den 15 december 2005.



Figur 49: Frekvensavvikelsen under kvällsavlastningen

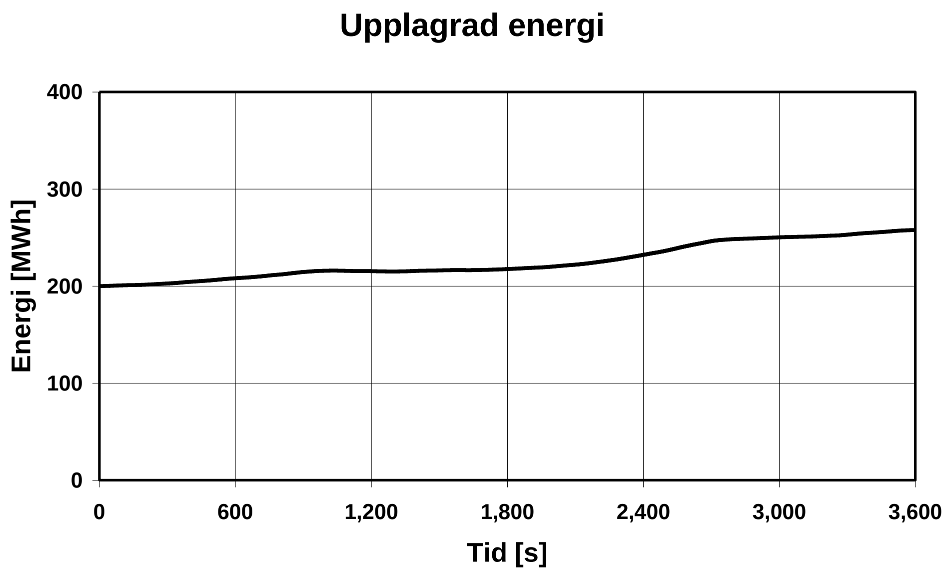
Figur 50 visar effektutmatningen från frekvensreglerreserven under samma antagande som ovan.



Figur 50: Uteffekt från frekvensreglerreserven

Den lägsta och högsta effektutmatningen är lika med -203 respektive 25 MW.

Figur 51 visar den upplagrade energin under timmen.



Figur 51: Upplagrad energi

Den lägsta och högsta upplagrade energin är lika med 200 respektive 258 MWh och skillnaden är lika med 58 MWh

Den tillåtna tidsavvikelsen är ±30 sekunder vilket innebär att det skulle vara tänkbart att driva systemet med en konstant frekvensavvikelse om 0,1 Hz i drygt 8 timmar för att komma från en tidsavvikelse om -30 till +30 sekunder eller omvänt. Detta skulle i sin tur innebära att frekvensreglerreserven skulle mata in eller ta ut 250 MW under denna tid och ändringen av upplagrad energi blir drygt 2 000 MWh. I verkligheten torde man inte köra systemet så hårt och den maximala ändringen under en timme av den upplagrade energin för de tre betraktade timmarna den 15 december 2005 har beräknats till 123 MWh.

4.6 Snabb aktiv störningsreserv

För att återställa den momentana störningsreserven efter ett produktionsbortfall och återställa beredskapen inför ett nytt produktionsbortfall ställer man inom Nordel kravet att det ska finnas en snabb störningsreserv som kan aktiveras inom 15 minuter efter ett produktionsbortfall. Storleken på den snabba störningsreserven ska vara minst lika stor som det dimensionerande produktionsbortfallet, det vill säga 1 200 till 1 600 MW. Aktiveringstiden ska vara kortare än 15 minuter och uthålligheten längre än 4 timmar. Den nödvändiga lagringskapaciteten för hela den snabba störningsreserven blir då 4 800 till 6 400 MWh. Den snabba störningsreserven består normalt av driftklara, stillastående vattenkraftaggregat och gasturbiner. Om anläggningar för energilagring ska användas som snabb aktiv störningsreserv måste de kunna konkurrera med tillgängliga driftklara, stillastående vattenkraftaggregat och gasturbiner.

4.7 Produktionsoptimering

Utöver ovan beskrivna användningsområden kan anläggningar för energilagring användas för produktionsoptimering, dvs. att mata in energi till energilagret när spotpriset är lågt och mata ut energi från energilagret när priset är högt, se Figur 10 och Figur 11. Det är en utmaning att bestämma styrstrategin för ett energilager under förutsättningen att det framtida spotpriset inte är känt.

För att få en uppfattning om nyttan av energilagring har spotpriset för år 2007 använts. Anläggningen för energilagring antas ha en märkeffekt $P_n = 1$ MW och en tillräckligt stor lagringskapacitet för att kunna tillämpa följande enkla strategi:

$$\begin{aligned} &P(k) = -P_n \quad om\, C(k) < (1-m)C_{ref} \\ &P(k) = 0 \quad om\, C_{ref}(1-m) < C(k) < (1+m)C_{ref} \\ &P(k) = +P_n \quad om\, C(k) > (1+m)C_{ref} \end{aligned} \qquad \textbf{(3)}$$

Ekvation (3) beskriver den enkla strategin: mata in effekten $P(k) = P_n$ till energilagret om spotpriset $C(k)$ för den aktuella timmen är lägre än $(1-m)C_{ref}$ och mata ut effekten $P(k) = P_n$ från energilagret om spotpriset

$C(k)$ för den aktuella timmen är högre än $(1+m)C_{ref}$. Parametern C_{ref} väljs så att den upplagrade energin vid periodens slut är lika med den upplagrade energin vid perioden början. Denna enkla strategi förutsätter att det framtida spotpriset är känt eller kan uppskattas med god noggrannhet. Strategin ger därför en övre gräns för det ekonomiska utbytet av driften av anläggningen för energilagret och en undre gräns för den nödvändiga lagringskapaciteten.

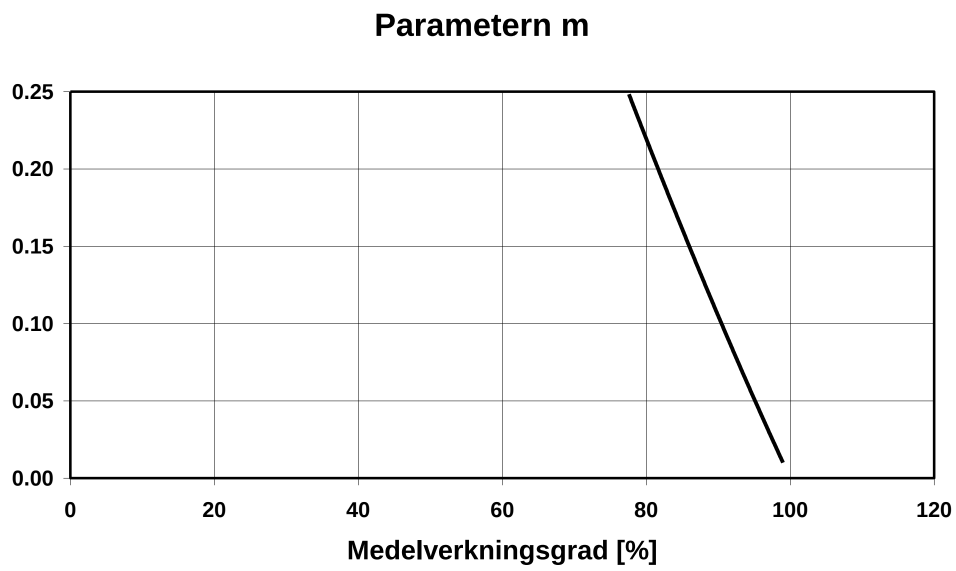
Parametern m väljs så att ägaren aldrig förlorar på att mata in energi till lagret och senare mata ut energin igen. Parametern m måste väljas med tanke på att energiomvandlingen från växelström till upplagrad energi är förknippad med förluster och att energiomvandlingen från upplagrad energi till växelström också är förknippad med förluster. Vi antar här att verkningsgraden vid inmatning av energi till lagret är lika med η_1 och att verkningsgraden vid energiutmatning från lagret är lika med η_2. Då blir det geometriska medelvärdet η av de båda verkningsgraderna lika med $\sqrt{\eta_1\eta_2}$ och vid gränserna för köp och försäljning måste villkoret i ekvation (4) gälla.

$$\frac{(1-m)C_r}{\eta_1} = (1+m)C_r\eta_2 \qquad \textbf{(4)}$$

Detta ger sedan ett värde på parametern m enligt ekvation (5) nedan.

$$m = \frac{1-\eta^2}{1+\eta^2} = \frac{1-\eta_1\eta_2}{1+\eta_1\eta_2} \qquad \textbf{(5)}$$

Figur 52 visar parametern m som funktion av medelverkningsgraden. Observera att den verkningsgrad som anges för energilager ibland är lika med $\eta_1\eta_2$.

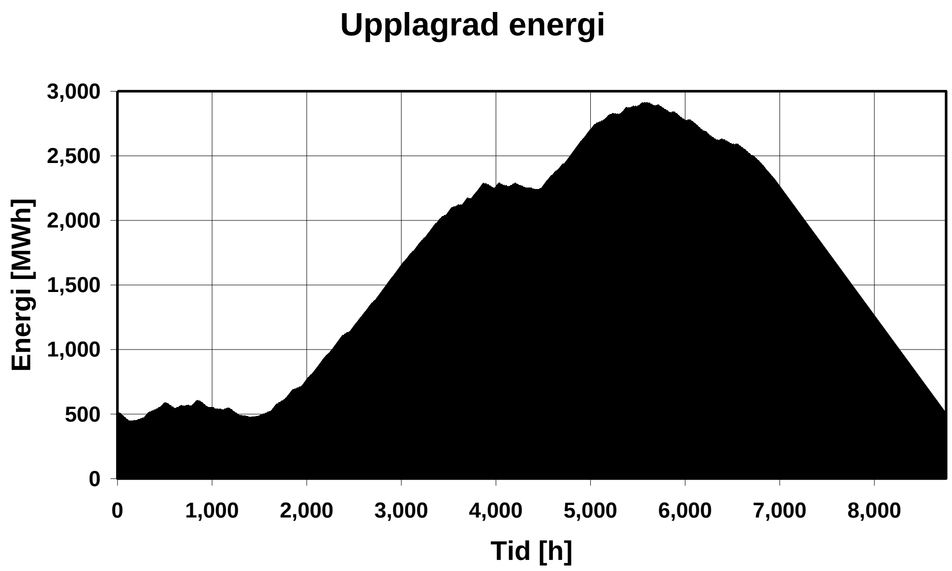


Figur 52: Parametern *m* som funktion av medelverkningsgraden

Om medelverkningsgraden är lika med 90 % blir parametern m lika med 0,105 och om medelverkningsgraden är 80 % blir parametern m lika med 0,220.

4.7.1 Optimering på årsbasis

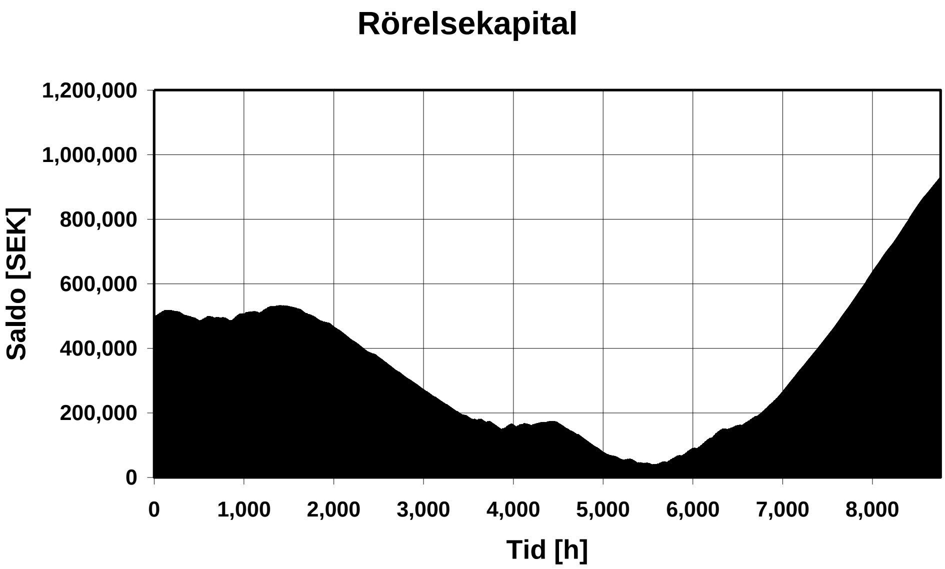
Med en medelverkningsgrad om 90 %, den ovan angivna strategin och spotpriset i Figur 10 kommer den upplagrade energin att variera på det sätt som visas i Figur 53. Begynnelsevärdet på den upplagrade energin har valts godtyckligt.



Figur 53: Upplagrad energi under år 2007

Den minimalt och maximalt upplagrade energin uppgår till 442 respektive 2 910 MWh och variationsbredden är lika med 2 468 MWh.

Det ekonomiska resultatet av ovan beskrivna strategi för driften av anläggningen framgår av Figur 54 nedan. Begynnelsevärdet på saldot är valts godtyckligt.

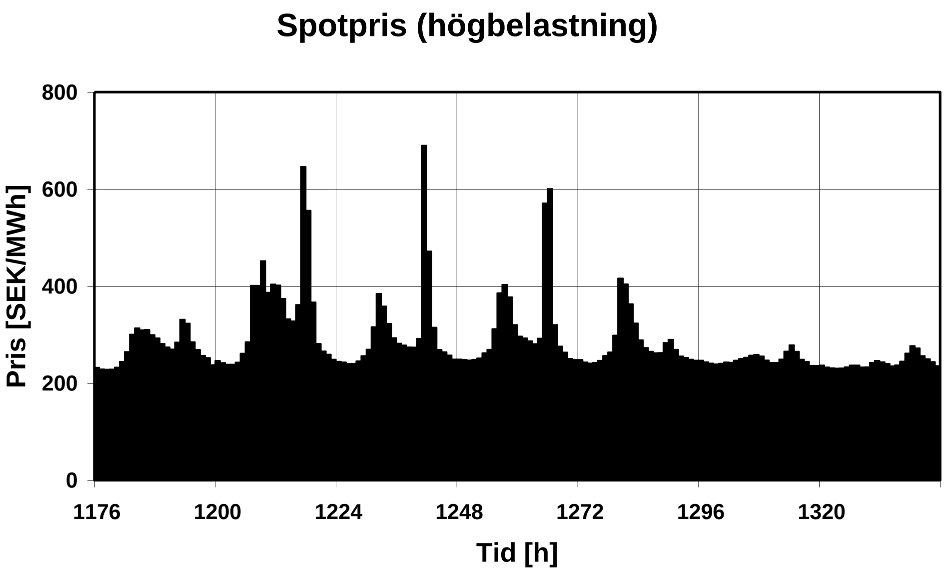


Figur 54: Rörelsekapital under år 2007

Det minimala och maximala saldot uppgår till 37 respektive 930 kSEK och det nödvändiga rörelsekapitalet är lika med 893 kSEK. Det ekonomiska resultatet av ett års drift av anläggningen för energilagring enligt strategin ovan uppgår till 430 kSEK (2007).

4.7.2 Optimering under en höglastvecka

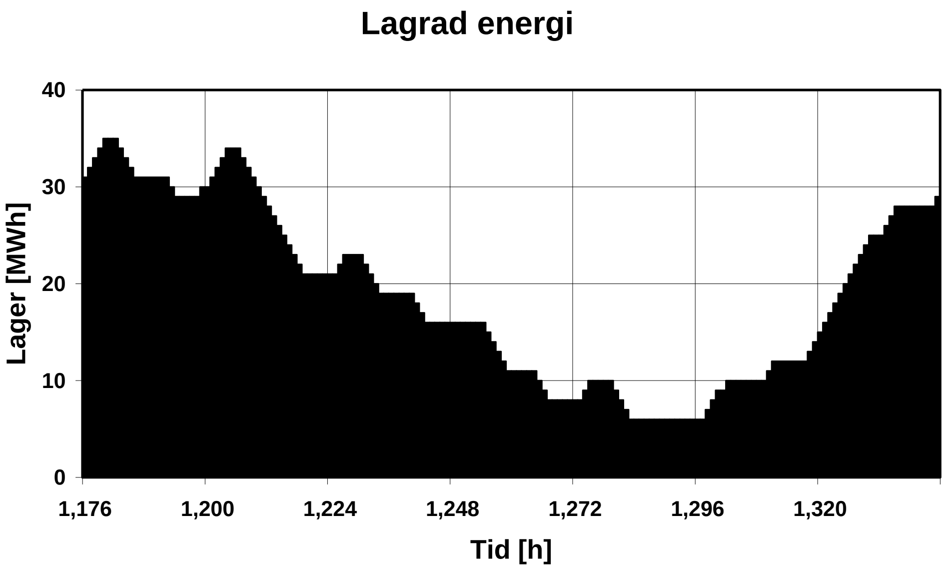
I stället för att optimera på årstidsbasis är det möjligt att optimera på veckobasis och då kommer det ekonomiska resultatet att variera under året. För att få en uppfattning om nyttan med energilagring på veckobasis studeras nedan en vecka med hög belastning, se Figur 2. Figur 55 visar spotpriset under denna vecka med hög belastning.



Figur 55: Spotpriset under en höglastvecka år 2007

Det lägsta och högsta spotpriset är 228 respektive 690 SEK/MWh.

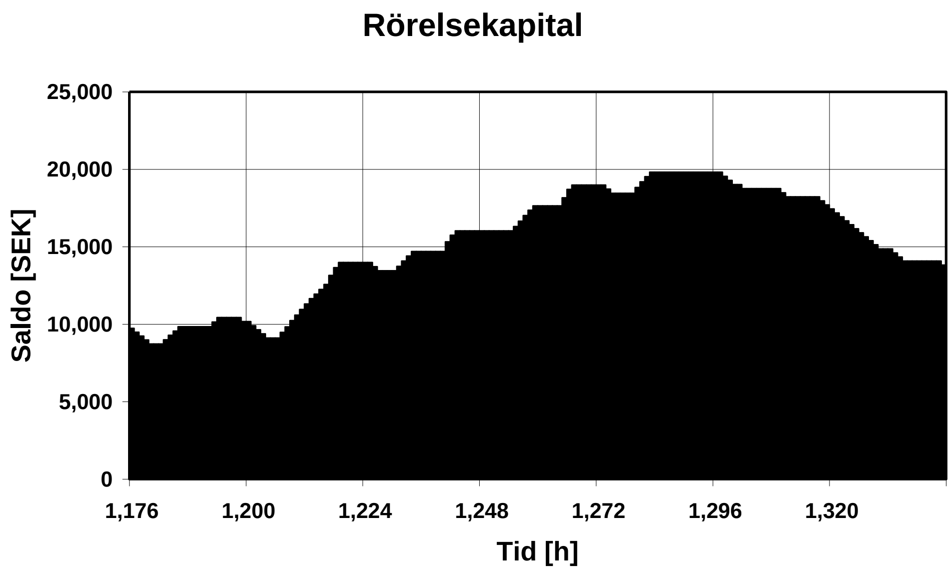
Med den ovan angivna strategin och spotpriset i Figur 55 kommer den upplagrade energin att variera på det sätt som visas i Figur 56 nedan.



Figur 56: Lagrad energi under en höglastvecka år 2007

Den lägsta och högsta lagrade energin är 6 respektive 35 MWh medan variationsbredden är 29 MWh

Det ekonomiska resultatet av ovan beskrivna strategi för driften av anläggningen för energilagring framgår av Figur 57 nedan.

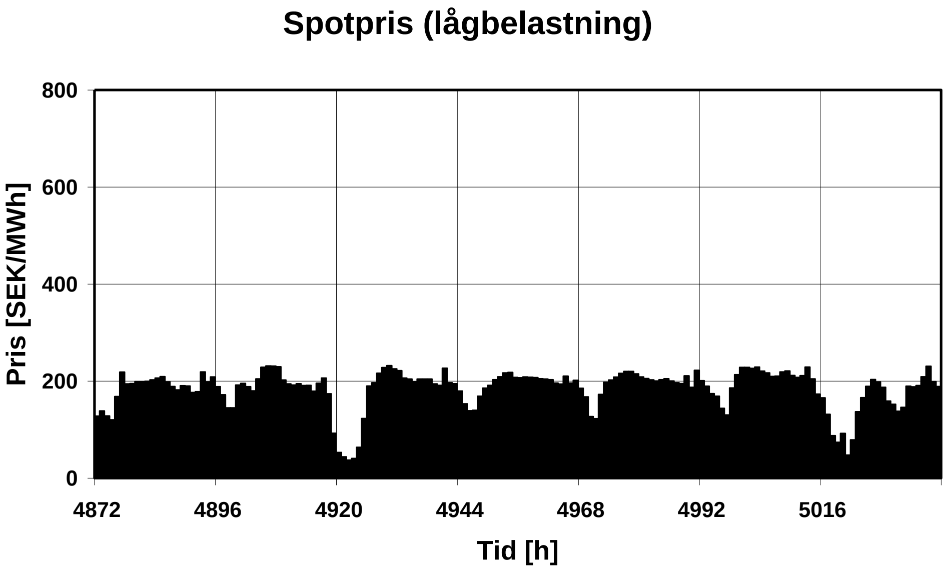


Figur 57: Rörelsekapital under en höglastvecka år 2007

Det lägsta och högsta saldot uppgår till 8 734 respektive 19 819 SEK och det nödvändiga rörelsekapitalet är lika med 11 085 SEK. Det ekonomiska resultatet av en veckas drift av anläggningen för energilagring enligt strategin ovan uppgår till 3 826 SEK (höglastveckan 2007).

4.7.3 Optimering under en låglastvecka

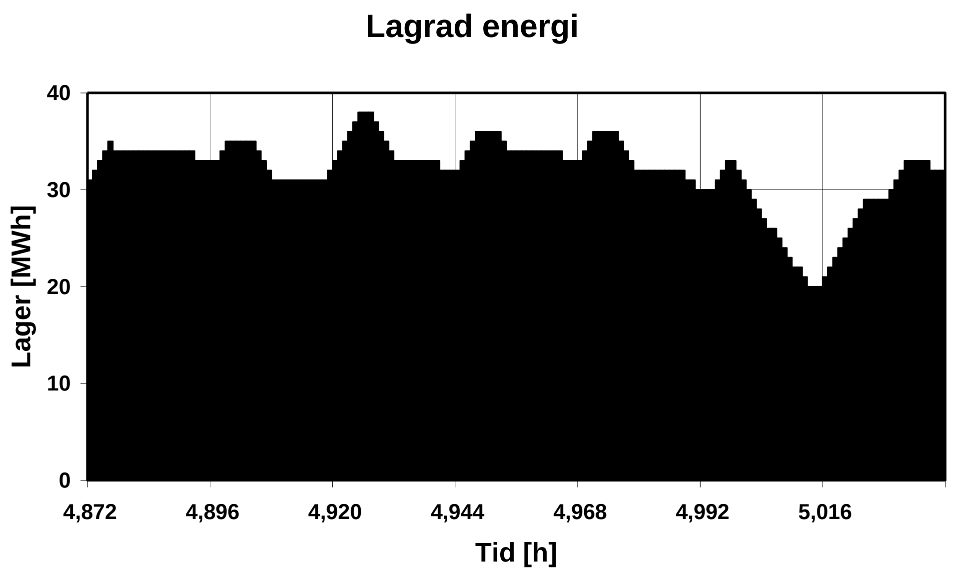
Nedan studeras en vecka med låg belastning, se Figur 3. Figur 58 visar spotpriset under denna vecka med hög belastning.



Figur 58: Spotpriset under en låglastvecka år 2007

Det lägsta och högsta spotpriset är 38 respektive 232 SEK/MWh.

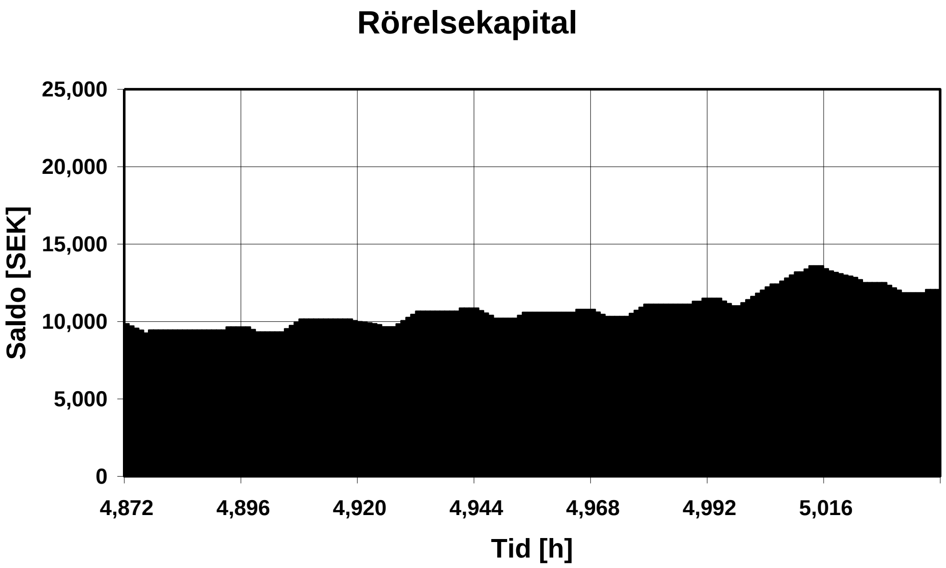
Med den ovan angivna strategin och spotpriset i Figur 58 kommer den upplagrade energin att variera på det sätt som visas i Figur 59 nedan.



Figur 59: Lagrad energi under en låglastvecka år 2007

Den lägsta och högsta lagrade energin är 20 respektive 38 MWh medan variationsbredden är 18 MWh.

Det ekonomiska resultatet av ovan beskrivna strategi för driften av anläggningen för energilagring framgår av Figur 60 nedan.



Figur 60: Rörelsekapital under en låglastvecka år 2007

Det lägsta och högsta saldot uppgår till 9 248 respektive 13 592 SEK och det nödvändiga rörelsekapitalet är lika med 4 343 SEK. Det ekonomiska resultatet av en veckas drift av anläggningen för energilagring enligt strategin ovan uppgår till 2 065 SEK (låglastveckan 2007).

4.7.4 Summering

Det ekonomiska resultatet av ett års (2007) drift av anläggningen för energilagring baserat på ovanstående enkla strategi uppgår till 521 kSEK. Med en kapitaliseringsfaktor om 10 blir nuvärdet av denna penningström lika med 5,2 MSEK, vilken skall ställas i relation till investeringskostnaden för ett energilager med en märkeffekt om 1 MW och en lagringskapacitet om cirka 2 500 MWh.

Det ekonomiska resultatet av en veckas drift, under en höglastvecka år 2007, av anläggningen för energilagring uppgår till 3 826 SEK. Det ekonomiska resultatet av en veckas drift, under en låglastvecka år 2007, av anläggningen för energilagring uppgår till 2 065 SEK. Resultatet av ett års drift av ett veckolager kan, mycket grovt, uppskattas till 52×(3 826+2 2065)/2=153 166 SEK.

Med en kapitaliseringsfaktor om 10 blir nuvärdet av denna penningström lika med 1,532 MSEK, vilken skall ställas i relation till investeringskostnaden för ett energilager med en märkeffekt om 1 MW och en lagringskapacitet om cirka 30 MWh.

Tabell 2 visar resultatet av en känslighetsanalys med avseende på medelverkningsgrad.

Tabell 2: Känslighetsanalys

Verkningsgrad	**85 %**	**90 %**	**95 %**
Ekonomiskt resultat [SEK] årsbasis	341 561	430 045	531 198
Ekonomiskt resultat [SEK] höglastvecka	3 029	3 826	5 605
Ekonomiskt resultat [SEK] låglastvecka	1 716	2 065	3 213

Verkningsgraden vid energiomvandlingen har mycket stor inverkan på det ekonomiska resultatet. I praktiken kommer det ekonomiska resultatet av energilagringen att bli lägre än vad som beräknas ovan på grund av att det framtida spotpriset inte är känt.

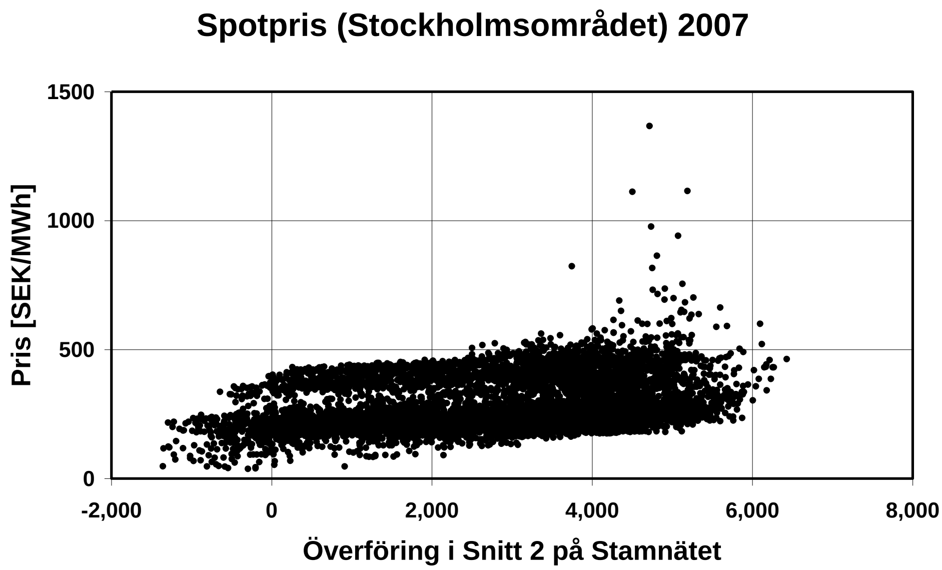
4.8 Ändring av överföringsförmågan och förluster

Överföringsförmågan på det svenska transmissionsnätet (Stamnätet) är inte konstant utan beror på en rad omständigheter. Om någon 400 kV ledning från norr till söder tas ur drift sjunker överföringsförmågan på Stamnätet. Överföringsförmågan beror även på tillgången på reaktiv effekt i södra Sverige. Överföringsförmågan från norr till söder brukar anges som en gräns för den tillåtna överföringen i ett antal snitt. Snitt 2 är en tänkt linje från öst till väst som går ungefär vid Gävle och Mora. Den tillåtna överföringen i Snitt 2 brukar vara cirka 7 000 MW, se referens [3] och [5].

När man betraktar Figur 7 förefaller det som om ett energilager i södra Sverige inte skulle vara av något större värde med tanke på att den högsta överföringen i Snitt 2 på Stamnätet var 6 428 MW och överföringsförmågan är omkring 7 000 MW. Från allmänt tillgängliga uppgifter är det svårt att avgöra i vilken utsträckning Svenska Kraftnät har gjort motköp i södra Sverige för att hålla nere överföringen i Snitt 2 på Stamnätet. En fördjupad analys skulle kunna belysa nyttan av ett energilager i södra Sverige.

Enligt referens [8] var förlusterna på stamnätet under år 2007 lika med 2,8 TWh och den högsta förlusteffekten under 2007 lika med 634 MW. Under år 2007 uppgick kostnaderna för förlusterna till 634 MSEK.

En anläggning för energilagring i södra Sverige skulle kunna minska förlusterna på Stamnätet genom att flytta överföringen från högbelastningstid till lågbelastningstid för överföringen i Snitt 2 på Stamnätet. Det finns en viss samvariation av spotpriset i Stockholmsområdet och överföringen i Snitt 2 på Stamnätet.



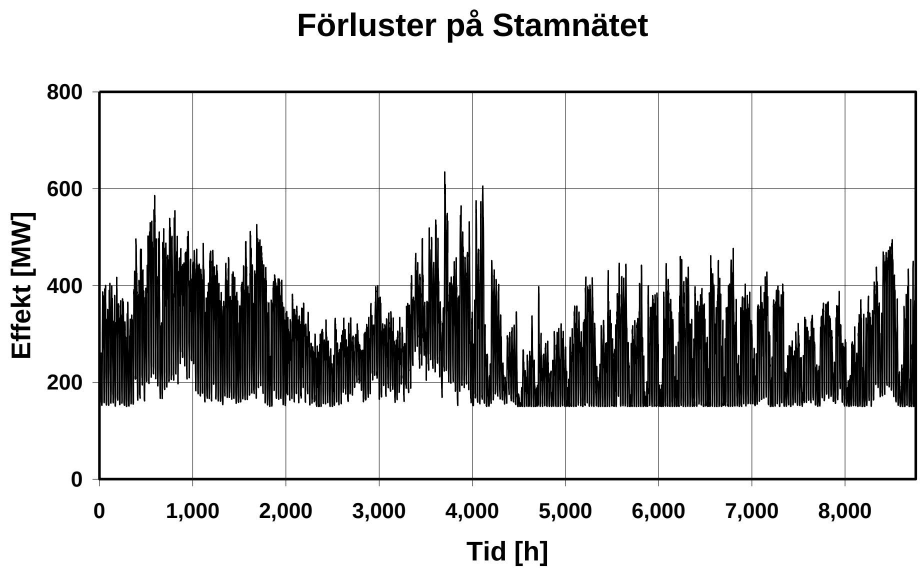
En ägare av en anläggning för energilagring i södra Sverige skulle därför kunna använda följande mycket förenklade strategi för driften av anläggningen. Köp energi och ladda energilagret om överföringen på Stamnätet är hög: Sälj energi och ladda ur energilagret och överföringen på Stamnätet är hög. För att ägaren av anläggningen för energilagret ska få full betalning för driften av anläggningen krävs någon form av avtal eller överenskommelse med Svenska Kraftnät om ersättning för de minskade förlusterna på Stamnätet.

Här gör vi det kraftigt förenklande antagandet att förlusterna P_f [MW] på Stamnätet kan skrivas som en summa av tomgångsförlusterna P_0 [MW] och belastningsförlusterna P_1 vid en överföring om 7 000 MW i Snitt 2 på Stamnätet. Dessutom antas att belastningsförlusterna är proportionella mot kvadraten på överföringen i Snitt 2 på Stamnätet.

$$P_f = P_0 + P_1 \left(\frac{P_t}{7000} \right)^2 \tag{6}$$

En enkel kurvanpassning ger att $P_0 = 150$ MW och $P_1 = 575$ MW.

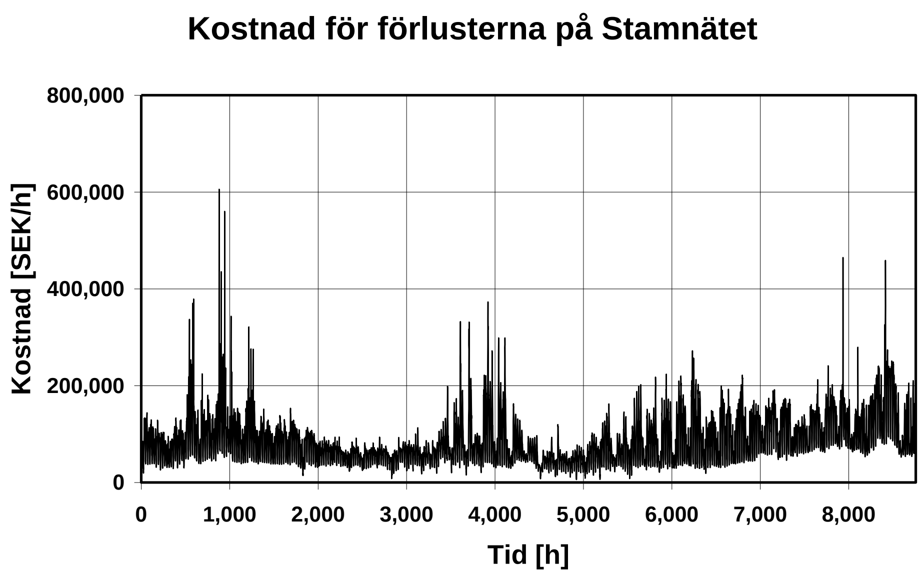
Figur 61 visar approximationen av förlusterna på Stamnätet under år 2007.



Figur 61: Förluster på Stamnätet

Approximationen ger en maximal effektförlust om 635 MW och en energiförlust om 2,4 TWh under år 2007.

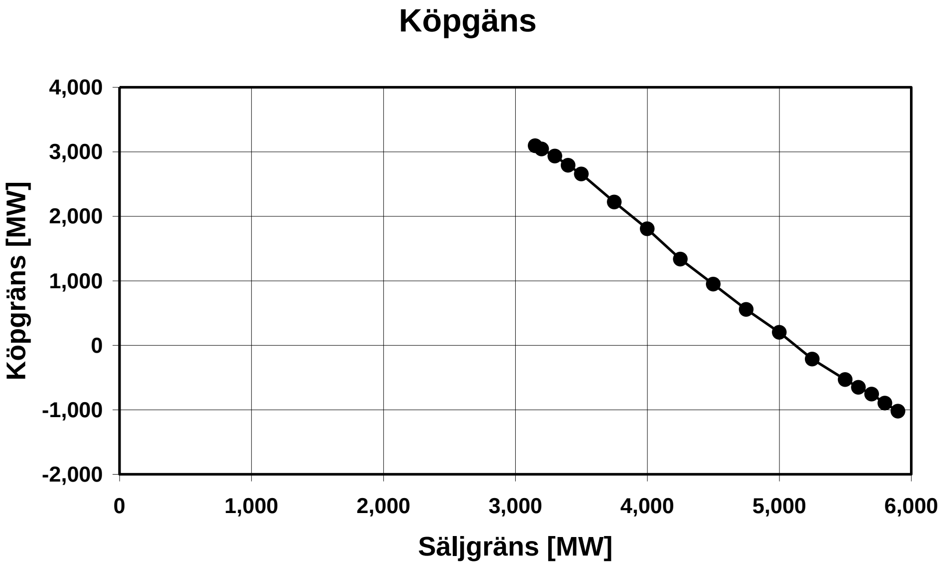
Dessutom antar vi att kostnaderna för förlusterna är proportionella mot produkten av förlusteffekten och spotpriset och får då förlustkostnaden som visas i Figur 62



Figur 62: Kostnad för förlusterna på Stamnätet

En kraftigt förenklad modell för driften av anläggningen för energilagret kunde vara att sälja när överföringen i Snitt 2 på Stamnätet är högre än en säljgräns

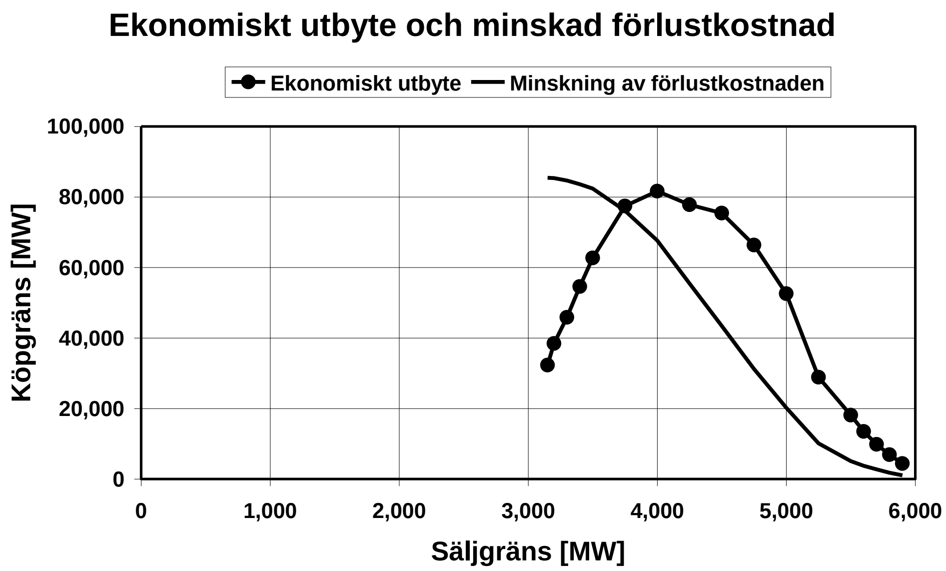
P_s [MW] och köpa när överföringen är lägre än en köpgräns P_k [MW]. Säljgränsen är en fri variabel och köpgränsen bestäms av säljgränsen och kravet att slutvärdet på den upplagrade energin ska vara lika med begynnelsevärdet på den upplagrade energin. Figur 63 visar hur köpgränsen beror av säljgränsen i ovan beskrivna strategi.



Figur 63: Köpgräns

Om man väljer att sälja endast när överföringen från norr till söder i Snitt 2 på Stamnätet är högre än 5 500 MW räcker det att köpa när överföringen från söder till norr är större än 532 MW. Om man väljer att sälja endast när överföringen från norr till söder i Snitt 2 på Stamnätet är högre än 3 500 MW räcker det att köpa när överföringen från norr till söder är mindre än 2 654 MW.

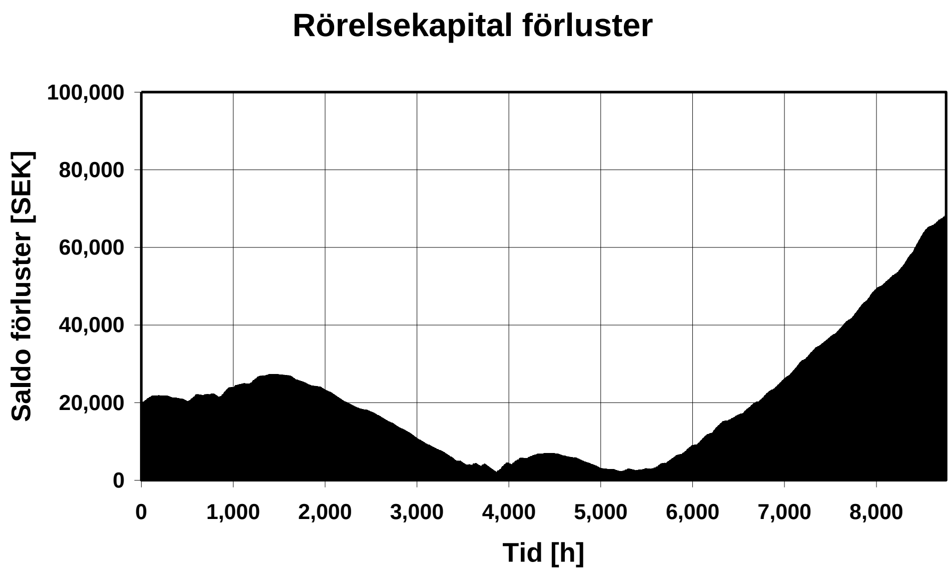
Det ekonomiska resultatet och de minskade kostnaderna för förluster av ovan beskrivna strategi för driften av anläggningen framgår av Figur 64 nedan.



Figur 64: Ekonomiskt resultat och minskad kostnad för förluster

Det bästa ekonomiska resultatet av ett års drift av anläggningen för energilagring enligt strategin ovan uppgår till cirka 80 kSEK (2007) vilket ska jämföras med de 430 kSEK som blev resultatet av produktionsoptimering i avsnitt 4.7. Att enbart låta överföringen i Snitt 2 på Stamnätet styra uppladdning och urladdning av energilagret förefaller inte var en framgångsrik strategi.

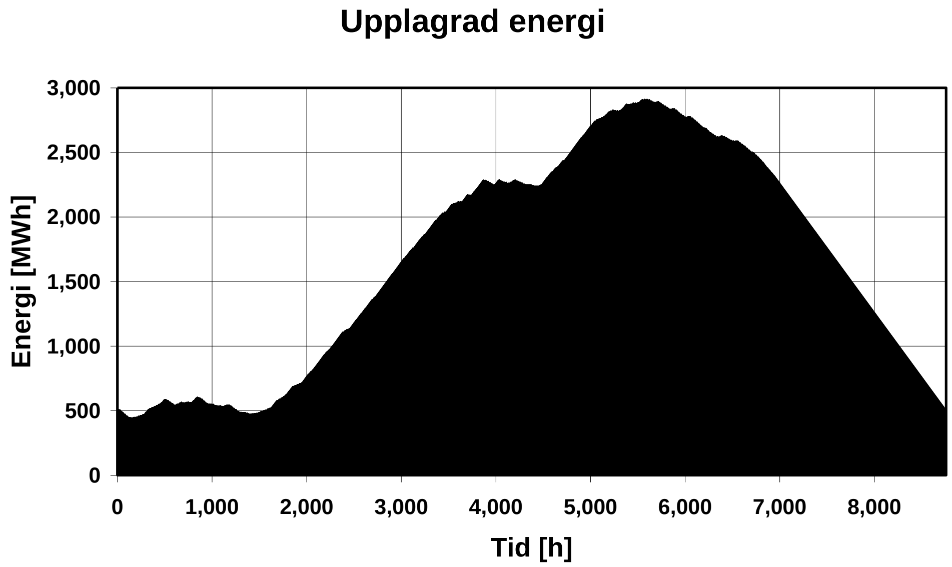
Anta nu att ägaren av anläggningen för energilagring får ersättning från Svenska Kraftnät för minskade förluster på Stamnätet och får betala ersättning för ökade förluster. Anta dessutom att ersättningen är lika med produkten av ändringen av förlusterna gånger spotpriset. Det ekonomiska resultatet av förlustersättningen vid driften av anläggningen enligt samma strategi som beskrevs i avsnitt 4.7 framgår av Figur 65 nedan. Begynnelsevärdet på saldot är valts godtyckligt.



Figur 65: Rörelsekapital för förlustersättning under år 2007

Det minimala och maximala saldot uppgår till 2 respektive 68 kSEK och det nödvändiga rörelsekapitalet är lika med 66 kSEK. Det ekonomiska resultatet av ett års drift av anläggningen för energilagring enligt strategin ovan uppgår till 48 kSEK (2007). Samvariationen hos spotpris och överföring på Stamnätet gör att en strategi baserad enbart på spotpriset även reducerar kostnaden för förlusterna på Stamnätet med nästan 50 %.

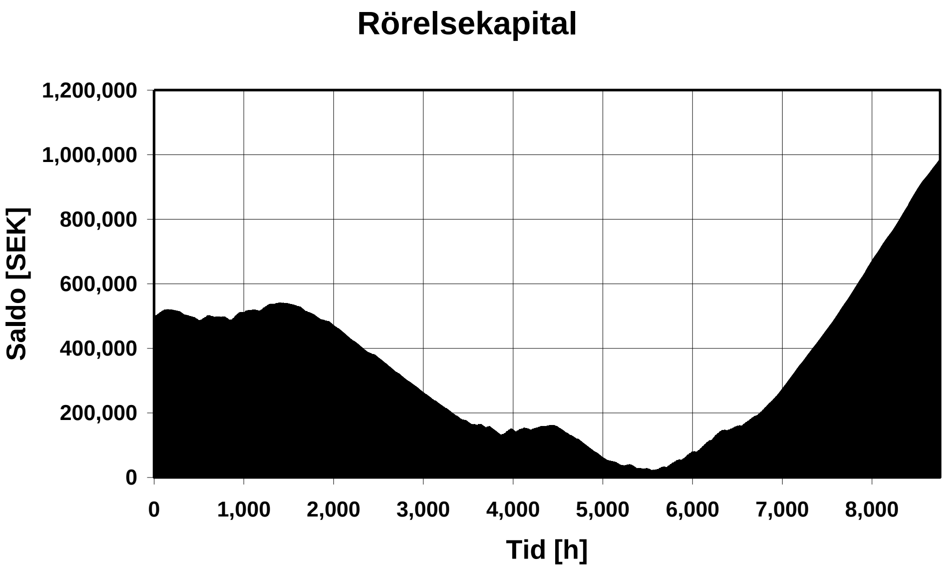
Med en medelverkningsgrad om 90 %, den ovan angivna strategin och spot-priset i Figur 10 kommer den upplagrade energin att variera på det sätt som visas i Figur 66. Begynnelsevärdet på den upplagrade energin har valts godtyckligt.



Figur 66: Upplagrad energi under år 2007

Den minimalt och maximalt upplagrade energin uppgår till 442 respektive 2 910 MWh och variationsbredden är lika med 2 468 MWh.

Det ekonomiska resultatet av ovan beskrivna strategi för driften av anläggningen framgår av Figur 67 nedan. Begynnelsevärdet på saldot är valts godtyckligt.



Figur 67: Rörelsekapital under år 2007

Det minimala och maximala saldot uppgår till 20 respektive 978 kSEK och det nödvändiga rörelsekapitalet är lika med 958 kSEK. Det ekonomiska resultatet av ett års drift av anläggningen för energilagring enligt strategin ovan uppgår till 478 kSEK (2007).

5 Energilagring i batterier

Laddningsbara batterier (ackumulatorer) finns i många olika utföranden och används i många olika applikationer.

5.1 Nuvarande utvecklingsnivå

Blybatterier (bly-syra) har använts under mycket lång tid, både som stationära batterier (hjälpkraft i transformatorstationer mm) och i traktionära tillämpningar (startbatterier i bilar, för el-truckar, med mera). Man har även utnyttjat laddningsbara batterier i elkraftsammanhang vilket har lett till viss nyutveckling. Det finns ett antal alternativ till de klassiska blybatterierna.

Bly-syra batterier har relativt lågt pris och är väl beprövade i såväl mobila applikationer (elbilar) som stationära applikationer såsom UPS-system. I vissa fall har bly-syra batterier använts i anläggningar för energilagring. En välkänd anläggning (Chino i USA) [5] är dimensionerad: 40 MWh och 10 MW. För bly-syra batterier kan man säga att verkningsgraden är beroende av hur snabbt upp/urladdning sker. Höga strömmar, det vill säga snabba omladdningsförlopp, ger stora förluster. Typisk verkningsgrad för Chino-anläggningen anges till 70 – 75 %. I detta fall har omladdningsförloppen varit relativt långsamma.

En typ av laddningsbara batterier har elektrolyt som cirkuleras med hjälp av pumpar (flow battery). Exempel på batterier med cirkulerande elektrolyt är:

- Polysulfid-Bromid (PSB) batterier: Verkningsgraden anges av Energy Storage Association [6] till cirka 75 %. Man rapporterar om två provanläggningar dels i Storbritannien: 15 MW, 120 MWh, och dels i USA: 12 MW, 120 MWh.
- Vanadium Redox (VRB) batterier: Verkningsgraden anges av Energy Storage Association [6] till cirka 85 %. Man rapporterar om provanläggning i Japan: 5 MWh, använd för spänningskvalitetsapplikation.
- Zink Bromid (ZnBr) batterier: Verkningsgraden anges av Energy Storage Association [6] till cirka 75 %. Anläggningar finns i drift i dag.

Bland andra lösningar kan följande nämnas:

Natrium Svavel (NaS) batterier. Eftersom elektroderna består av flytande svavel respektive natrium måste batteriet hålla hög temperatur (cirka 300 °C). Verkningsgraden anges av Energy Storage Association [6] till cirka 89 % det vill säga betydlig högre än ovan visade alternativ.

Litium-jon (Li-ion) batterier dominerar i dag när det gäller marknaden för små portabla batterier (mobiltelefoner med mera). Batteritypen har många positiva egenskaper, såsom hög energitäthet, hög verkningsgrad (nära 100 %) och relativt lång livstid (cirka 3000 upp/urladdningscykler med 80 % av kapaciteten). För de stora batterierna är problemet de stora tillverkningskostnaderna som anges till över 600 USD/kWh. Batteritypen kräver skyddskretsar för att begränsa ström och spänning.

5.2 Egenskaper

Batterilagring kännetecknas av följande:

- Livslängden för ett uppladdningsbart batteri är begränsat av antal upp- och urladdningar. Kapacitet och verkningsgrad försämras efter hand.
- Beroende på typ av laddningsbart batteri kan verkningsgraden, det vill säga kvoten mellan inmatad och återmatad energi, vara låg. Litium-jon batterier synes dock ha betydligt högre verkningsgrad än andra batterityper.
- I applikationer som innebär många omladdningar per tidsenhet begränsas livslängden.
- Olika batterityper har olika egenskaper varför applikationen kan vara avgörande för valet av batterityp.
- Snabbheten vid upp- och urladdning av batterier är begränsad, bland annat av batteriernas interna resistans. Upp- och urladdningstiden varierar mellan olika typer av batterier.

5.3 Forskning och utveckling

Man arbetar i dag med att reducera tillverkningskostnaden för Litium-jon batterier. Vidareutveckling av Litium-jon batterier pågår för att göra tekniken mer konkurrenskraftig. Livslängden, beträffande antal omladdningscykler, på batterier behöver förlängas.

Angående applikation av energilagring baserade på batterier finns följande uppslag för utvecklingsprojekt. Energilager baserade på batterier placeras perifert i distributionsnät. I normal drift underhållsladdas batterierna, det vill säga inga upp- och urladdningar görs. Vid planerad eller oplanerad frånkoppling från yttre nät kan batterilagret utgöra alternativ till ledningsreserv eller mobilt reservkraftaggregat.

5.4 Integrering i kraftsystemet

Batterilagring kräver kraftelektronik för laddning av batterierna och återmatning till kraftsystemet. Batterilager kan placeras relativt fritt i kraftsystemet vilket möjliggör applikationer där närhet till exempelvis störande belastning är viktig.

För energilagring i tidsskalan upp till ett dygn kan batterilager användas. I det nordiska kraftsystemet finns stor andel vattenkraftverk med dammar där dygnsreglering sker på ett effektivt sätt. Därför bedöms behovet av batterilager för detta ändamål vara litet i det svenska kraftsystemet.

Volymen laddningsbara batterier kommer att öka i samband med utveckling av bilparken till elbilar och elhybridbilar. Bilar som ansluts till elnätet för laddning skulle även kunna utnyttjas som elenergilager för kraftsystemets behov.

5.5 Ekonomisk värdering

Den ekonomiska värderingen av energilagring i batterier varierar mycket mellan olika typer av batterier [6]. Kostnaden kan delas upp i kapitalkostnad och kostnader på grund av effektförluster.

Litium-jon batterier har i dag stor investeringskostnad medan den goda verkningsgraden medför små kostnader för effektförluster.

Bly-syra batterier har relativt sett lägre investeringskostnader men låg verkningsgrad och begränsad livslängd påverkar kostnadsbilden negativt.

I dagsläget är det svårt att se energilagring i batterier som ett bra alternativ i applikationer med ofta förekommande omladdningscykler och stora energimängder som omladdas.

6 Energilagring i kraftkondensatorer

På senare år har man kunnat tillverka ”super”-kondensatorer för elkraftändamål. Detta har gett nya möjligheter för energilagring för vissa applikationer i kraftsystem.

6.1 Nuvarande utvecklingsnivå

Kondensatorer med kapacitans upp mot 2000 Farad är tillgängliga. Vidare kan kondensatorer upp- och urladdas i stort sett obegränsat antal cykler utan att livslängden påverkas. Snabb upp- och urladdning är möjlig och begränsas i stort sett enbart av kraftelektroniken för upp- och urladdning. För enbart kondensatorerna är verkningsgraden nära 100 %. För applikationer med stort effektbehov och litet energibehov är energilagring i kondensatorer ekonomiskt fördelaktig (cirka 200 USD/kW och 8 000 USD/kWh).

6.2 Egenskaper

Kondensatorlagring kännetecknas av följande:

- Livslängden för ett energilager baserat på kondensatorer är beträffande antal upp- och urladdningar betydligt längre än vad som gäller för batterilager.
- Verkningsgraden, det vill säga kvoten mellan inmatad och återmatad energi, är hög (nära 100 %) om man betraktar enbart kondensatorn.
- Ett kondensatorlager kan leverera stor effekt under kort tid. Däremot är energilagringskapaciteten begränsad.
- Energiinnehållet i en kondensator återspeglar sig i spänningen över kondensatorn. För att kunna få snabb upp- och urladdning vid låg grad av uppladdning, därmed vid låg spänning, krävs att strömriktaren för upp- och urladdning dimensioneras för så hög strömnivå så att önskad effektutmatning kan bibehållas även vid låg spänning.
- Lagringsmetoden är lämplig i applikationer där snabbhet är av betydelse, till exempel för spänningskvalitetsförbättring och för transient kraftsystemstabilitet.

6.3 Forskning och utveckling

Superkondensatorer kan, förutom energilagringskapacitet, anses ha överlägsna egenskaper jämfört med batterier. De tillgängliga superkondensatorerna anges kunna lagra ca 5 Wh/kg medan Litium-jon batterier kan lagra ca 140 Wh/kg. Eftersom energilagringskapaciteten i en kondensator är kraftigt beroende på ytan hos kondensatorn elektroder är forskningen inriktad på hur man skall kunna utöka denna yta. Här har tekniken med kol-nanorör visat sig vara lovande. Kommersiell produktion av superkondensatorer baserade på kol-nanorör bedöms starta inom 3 – 8 år (uppskattning gjord av professor Joel Schindall, MIT).

För kraftapplikationer vid hög spänning, där snabb reglering är betydelsefull, finns i dag FACTS-anläggningar (Flexible AC Transmission Systems) av olika typ STATCOM, SVC, med mera. Här har utvecklingen kommit långt. Dessa system betraktas inte som system för energilagring även om de i en kort tidsskala, det vill säga under en kraftfrekvensperiod, i realiteten lagrar en viss energimängd.

En svårighet som man identifierat med vindkraftverk är svårigheter att bibehålla driften av ett vindkraftverk vid nätstörningar (fault ride through). Med dagens teknik har man ofta ett system där man ”bränner bort” energin från vindkraftverket i ett resistivt motstånd när inte nätet kan ta emot denna energi. Ett alternativ till detta kan vara att lagra energin i ett kondensatorlager. Detta lager skulle kunna anslutas till de likspänningsmellanled som ofta finns i vindkraftverkens generatorsystem. Möjlighet till denna teknik och ekonomisk jämförelse med nu använd teknik kan vara ett uppslag för forskning/utveckling.

I konventionella kraftverk kan ett uppslag vara att ansluta ett kondensatorbaserat energilager till generatorskenan för att förbättra transient stabilitet vid kortslutning i yttre nät. Detta är i dag ett fenomen som kräver mycket snabb felbortkoppling av nätfel för att säkerställa stabilitet.

6.4 Integrering i kraftsystemet

Energilagring i kondensatorer kräver kraftelektronik för laddning av kondensatorerna och återmatning till kraftsystemet. Kondensatorlager kan placeras relativt fritt i kraftsystemet vilket möjliggör applikationer där närhet till exempelvis störande belastning är viktig. Den snabba responsen gör tekniken lämplig för applikationer där kortvarig och snabb respons är viktig. Exempel på detta är förbättring av transient stabilitet nära kraftverk, spänningskvalitetsförbättring, med mera. Den begränsade energilagringskapaciteten innebär att tekniken med lagring i kondensatorer inte är lämplig för utjämning av belastningsvariationer i minutskala och långsammare.

En intressant applikation för superkondensatorer är att kombinera dessa med batterilager. Därmed kan egenskaperna kombineras, d v s batteriernas möjlighet att lagra stora energimängder och kondensatorernas möjlighet att leverera stor effekt under kort tid. Därmed kan man minska batteriernas omladdningsfrekvens vilket kan ge förlängd livslängd hos dessa batterier.

6.5 Ekonomisk värdering

För applikationer som kräver stor effekt men liten energilagring görs bedömningen att energilagring i kondensatorer är ekonomiskt konkurrenskraftigt.

7 Energilagring i svänghjul

Energilagring i svänghjul är en gammal idé som ofta har använts för stabilisering av kraftsystem eftersom ett direkt inkopplat svänghjulssystem tillför tröghetsmoment i kraftsystemet.

Så länge svänghjulet baseras på konventionell teknik, främst beträffande de mekaniska lagren som håller rotorn på plats, har systemet vissa lagerförluster. Vidare kräver svänghjulslagring hög rotationshastighet och stor roterande massa för att kunna lagra tillräckligt stor rörelseenergi. Med traditionell lagerteknik fås stort slitage och därmed kort livslängd. Moderna svänghjulslager använder magnetiska lager där den rörliga delen ”svävar” på ett magnetfält varvid friktionen blir obefintlig.

Ett svänghjulsbaserat energilager kräver även att rotorn skall kunna variera varvtalet inom ett stort område eftersom upplagrad energi är proportionell mot varvtalet i kvadrat. För att kunna ansluta ett svänghjulsbaserat energilager till kraftsystemet (som har en i stort sett konstant frekvens) krävs en frekvensomriktare som kopplar svänghjulet till kraftsystemet.

7.1 Nuvarande utvecklingsnivå

Moderna energilager som baseras på svänghjul använder avancerade komponenter såsom magnetiska lager för rotorn och frekvensomriktare [2]. Lagringskapaciteten är relativt begränsad eftersom upplagring av stora energimängder i svänghjul kräver hög rotationshastighet och stor roterande massa.

7.2 Egenskaper

Energilagring med svänghjul kännetecknas av följande:

- Livslängden för ett energilager baserat på svänghjul är i stort sett obegränsad.
- Verkningsgraden, det vill säga kvoten mellan inmatad och återmatad energi, är hög (nära 90 %) inkluderande omriktaren.
- Ett energilager baserat på svänghjul kan leverera stor effekt under kort tid. Däremot är energilagringskapaciteten begränsad.
- Energiinnehållet i ett svänghjul återspeglar sig i rotationshastigheten. Strömriktaren måste därför kunna arbeta inom ett stort frekvensområde för svänghjulsgeneratorn.
- Lagringsmetoden är lämplig i applikationer där snabbhet är av betydelse, till exempel för spänningskvalitetsförbättring och för transient kraftsystemstabilitet.

7.3 Forskning och utveckling

Det hade varit värdefullt med ökad energilagringskapacitet. Detta kan ske om den roterande delen kan ges större massa och högre rotationshastighet. I stort är detta fråga om materialutveckling.

En svårighet som man identifierat med vindkraftverk är svårigheter att bibehålla driften av ett vindkraftverk vid nätstörningar (fault ride through). Med dagens teknik har man ofta ett system där man ”bränner bort” energin från vindkraftverket i ett resistivt motstånd när inte nätet kan ta emot denna energi. Ett alternativ till detta kan vara att lagra energin i ett energilager med svänghjul. Detta lager skulle kunna anslutas direkt till vindkraftverkens generatorsystem. Möjlighet till denna teknik och ekonomisk jämförelse med nu använd teknik kan vara ett uppslag för forskning/utveckling.

I konventionella kraftverk kan ett uppslag vara att ansluta ett energilager med svänghjul till generatorskenan för att förbättra transient stabilitet vid kortslutning i yttre nät. Kortslutning i yttre nät kräver i dag mycket snabb felbortkoppling för att säkerställa stabilitet.

7.4 Integrering i kraftsystemet

Energilagring i svänghjul kräver kraftelektronik för utbyte av energi med kraftsystemet. Energilager baserat på svänghjul kan placeras relativt fritt i kraftsystemet vilket möjliggör applikationer där närhet till exempelvis störande belastning är viktig. Den snabba responsen gör tekniken lämplig för applikationer där kortvarig och snabb respons är viktig. Exempel på detta är förbättring av transient stabilitet nära kraftverk, spänningskvalitetsförbättring, med mera. Den begränsade energilagringskapaciteten innebär att tekniken inte är lämplig för utjämning av belastningsvariationer i minutskala och långsammare.

7.5 Ekonomisk värdering

Bedömningar görs [6] att energilager med svänghjul är ekonomiskt konkurrenskraftiga i applikationer som kräver stor effektkapacitet och liten energikapacitet.

8 Energilagring i pumpkraftverk

Pumpkraftverk har funnits under lång tid. Ett pumpkraftverk är i grunden ett vattenkraftverk med möjlighet att pumpa upp vatten till en högre nivå för att därigenom lagra energi.

8.1 Nuvarande utvecklingsnivå

Tekniken med pumpkraftverk kan betraktas som mogen.

8.2 Egenskaper

Energilagring i pumpkraftverk kännetecknas av följande:

- Livslängden för ett pumpkraftverk är i samma storleksordning som för ett ”vanligt” vattenkraftverk, det vill säga minst 50 år.
- Verkningsgraden, det vill säga kvoten mellan inmatad och återmatad energi, är relativt hög (cirka 80 %).
- Ett pumpkraftverk kan leverera stor effekt under relativt lång tid beroende på magasinsstorlek och fallhöjd. Likaledes är energimängden som kan lagras beroende av magasinsstorlek och fallhöjd.
- Pumpkraftverket kräver inte strömriktare under full generatordrift, men strömriktare krävs normalt för start till pumpdrift.
- Lagringsmetoden kan användas både i applikationer som kräver relativt snabb respons vid effektändring (till exempel frekvensreglering) och vid långvariga regleringsfunktioner (lastutjämning).
- Beroende på var i nätet ett pumpkraftverk kan placeras kan det användas för utjämning av effektöverföring i kraftnätet. I Sverige sker ofta stor effektöverföring från norr till söder. Denna överföring varierar

kraftigt under dygnet. Om man kan placera pumpkraftverk i södra Sverige kan dessa lagra energi nattetid (låglasttid) genom effekt från norr för att sedan avlasta förbindelserna dagtid (höglasttid).

8.3 Forskning och utveckling

Ett problem med nuvarande pumpkraftverk är att de måste placeras där geografin ger naturliga förutsättningar:

- Tillgång på vatten
- Naturligt övre vattenmagasin
- Naturligt nedre vattenmagasin

I många fall är de två första förutsättningarna uppfyllda i många befintliga vattenkraftverk. Däremot är ofta det nedre magasinet ”icke existerande”. Man har i vissa fall studerat möjligheterna att ”konstruera” nya vattenmagasin. En sådan möjlighet som diskuterats är att bygga bergrum, det vill säga spränga ut bergrum under marknivå för att skapa det ”nedre” vattenmagasinet. I vissa fall kan det vara möjligt att utnyttja befintliga skapade vattenmagasin:

- Nedlagda gruvor där stora underjordiska ”tomrum” finns där malmen brutits ut.
- Underjordiska beredskapslager för olja som inte längre används.

Det finns behov av kartläggning i Sverige var pumpkraftverk kan placeras, företrädesvis i söder. I en sådan kartläggning bör man göra en ekonomisk kalkyl av nyttan i varje enskilt fall. Här finns troligen behov av en mall för en sådan kalkyl.

8.4 Integrering i kraftsystemet

Pumpkraftverk måste placeras där de naturliga hydrologiska förutsättningarna finns. Detta i sin tur kan medföra att etablering av pumpkraftverk även medför behov av nya ledningar.

Förutom ekonomisk vinst genom lastutjämning kan pumpkraftverk användas för minskning av maximalt överföringsbehov i stamnätet, regionnät och lokalnät. Detta kan resultera i senareläggning av ledningsutbyggnader.

8.5 Ekonomisk värdering

I likhet med konventionella vattenkraftverk innebär byggandet av pumpkraftverk stora investeringar. Investeringskostnaden är i hög grad beroende av de naturliga förutsättningarna, det vill säga tillgång till naturliga magasin och närhet till lämpliga anslutningspunkter i kraftsystemet. Man kan dock jämföra kostnaderna för pumpkraftverk med att bygga ”energineutrala” HVDC-länkar till kontinenten.

9 Energilagring genom vätgasgenerering

Energi lagras genom att generera vätgas till exempel genom elektrolys och att komprimera gasen. El produceras i en bränslecell eller gasmotor plus roterande generator.

9.1 Nuvarande utvecklingsnivå

Metoder att producera vätgas är kända. Dock arbetas på en del nya metoder, däribland artificiell fotosyntes [3].

9.2 Egenskaper

Vätgas kan produceras genom elektrolys av vatten vilket kan beskrivas:

$2H_2O$ + elektricitet $\rightarrow 2H_2 + O_2$

Vätgas har lågt energiinnehåll per volymsenhet (cirka en tredjedel jämfört med biogas). Detta innebär att man vill lagra vätgas vid högt tryck, vilket ger stora krav på material för lagring, distribution, med mera.

Energilagring med vätgas kännetecknas av följande:

- Verkningsgraden, det vill säga kvoten mellan inmatad och återmatad energi, är relativt låg (några siffror på detta är svåra att finna). En uppskattning är att elektrolysen i sig har en verkningsgrad på 80 % men att komprimering och lagring kommer att ge ytterligare förluster, ungefär lika mycket.
- Vätgasen har relativt lågt energiinnehåll per volymsenhet jämfört med till exempel biogas.
- Vid återmatning till kraftsystemet kan detta ske genom bränsleceller eller med konventionella termiska kraftverkstyper.
- Själva vätgastillverkningen är troligen en process som bör ske med, i stort sett, konstant effekt. Däremot är återmatningen till nätet beroende av vilken teknik som används.
- En svårighet med vätgaslagring är att göra kringsystemen med komprimering av gasen och lagring av gasen på ett säkert och effektivt sätt. Många lagringssätt medför läckage av vätgasen.

Troligen har vätgaslagring sin största potential i fordon där elenergin överförs till fordonet som vätgas i stället för laddning av batterier.

9.3 Forskning och utveckling

Kompression och lagring av vätgas anges som områden där ytterligare utveckling behövs.

9.4 Integrering i kraftsystemet

Energilagring i form av vätgas kräver anläggning för produktion av vätgas (omvandling från elenergi), lagring av vätgas och omvandling av vätgas till elenergi. Energilager baserade på vätgas kan placeras relativt fritt i kraftsystemet vilket möjliggör applikationer där närhet, exempelvis till störande belastning är viktig.

Den begränsade energilagringskapaciteten innebär att tekniken inte är lämplig för utjämning av långsamma belastningsvariationer.

9.5 Ekonomisk värdering

Uppgifter om detta har vi inte funnit.

10 Energilagring genom luftkomprimering

Vid perioder med produktionsöverskott i kraftsystemet drivs synkronmaskinen (motor/generatoraggregatet) som motor och driver en kompressor som pumpar luft till ett lagringsutrymme för tryckluft. Detta lagringsutrymme är normalt underjordiskt. Vid perioder med produktionsunderskott i kraftsystemet leds den komprimerade luften till en brännkammare där bränslet förbränns och den varma gasen driver turbin som i sin tur är ansluten till synkronmaskinen (motor/generatoraggregatet).

10.1 Nuvarande utvecklingsnivå

Som det används i dag är detta system främst användbart i kraftsystem med gasturbinanläggningar. Tekniken används främst för att effektivisera processen genom att använda billig energi, producerad vid låglasttider, för kompressorbehovet i gasturbinanläggningar.

Anläggningar för lagring av komprimerad luft har varit i drift under mer än 25 år. De områden som är i fokus för potentiella problem är relaterade till tryckluftlagret, som normalt är underjordiskt. Det handlar om risk för korrosion, termodynamiska problem samt långtidsstabilitet.

10.2 Egenskaper

Energilagring med tryckluft kännetecknas av följande:

- Verkningsgraden, det vill säga kvoten mellan inmatad och återmatad energi, är relativt låg.
- Främsta applikation är belastningsutjämning med gasturbindrift. Det har dock angetts att systemet kan användas som rullande reserv.
- Även om det inte finns så mycket gasturbiner i Sverige för energiproduktion kommer det troligen att finnas en del kombikraftverk med

kombination av gasturbin och ångturbin. I ett sådant kraftverk kan det vara av intresse att utnyttja tekniken med upplagrad tryckluft.

10.3 Forskning och utveckling

I det nuvarande konceptet utgår vi från att lågprisel i kraftsystemet används för komprimering av luft. Man kan undersöka möjligheterna att komprimera luft direkt från vindturbiner utan att gå vägen över elgenerering. Detta skulle kunna förbättra verkningsgraden och dessutom ge enklare vindkraftkonstruktioner.

Utgående från befintligt eller planerat kombikraftverk kan man undersöka möjligheten att nyttja vindkraft för luftkomprimering för vidare användning i kombikraftverk.

10.4 Integrering i kraftsystemet

Lagring av tryckluft måste placeras där det är lämpligt att bygga lagringsutrymmen för tryckluften, normalt underjordiska lager. Vidare bör anläggningen placeras där behovet finns i kraftsystemet.

10.5 Ekonomisk värdering

Bedömningar har gjorts [6] att systemet är relativt ekonomiskt gångbart.

11 Bedömt FoU-behov

Det pågår omfattande forskningsinsatser på olika områden beträffande olika tekniker, till exempel batteriteknik, för elenergilagring. Dessa utvecklingsinsatser går ofta ut på förbättring av verkningsgrad och livslängd.

Bedömningen görs att det i Sverige främst finns behov att utvärdera nyttan av elenergilagring i olika applikationer och att identifiera lämpliga metoder för energilagring för de olika applikationerna. De olika applikationerna för den lagrade elenergin bör utredas vidare beträffande nyttovärdering, kostnader, miljöpåverkan, med mera.

11.1 Kommersialisering

Här tar vi inte ställning till hur nya uppslag, som bedöms vara ekonomiskt lönsamma, skall kommersialiseras. Det krävs kapital för eventuella provanläggningar.

12 Pågående FoU-verksamhet

Forskning angående batterier, kondensatorer och svänghjulslagring pågår vid de svenska universiteten. Det kan finnas fler områden som inte identifierats i denna översiktliga rapport.

13 Möjligt utvecklingsscenario

Forsknings- och utvecklingsinsatser kan leda till ett antal förslag om uppförande av olika pilotanläggningar. Följande projektidéer kan vara aktuella att implementera:

- Pumpkraftverk för lastutjämning, frekvensreglering, störningsreserv samt som alternativ till ledningsutbyggnad.
- Batterilagring för elkvalitetsförbättring och som alternativ till ledningsreserv i distributionsnät.
- Energilager baserat på kondensatorer kopplat till kraftverk för förbättring av transient och dynamisk stabilitet.
- Energilager baserat på svänghjul kopplat till kraftverk för förbättring av transient och dynamisk stabilitet.
- Mycket annat baserat på idéer som föds under tidens gång. Erfarenhetsmässigt vet vi att alla uppslag för applikationer med mera inte finns när man startar forsknings- och utvecklingsarbete men att idéer föds.

13.1 Tidsskala

Under de närmaste åren (2 till 4 år framöver) bör konceptuella lösningar tas fram för de olika applikationerna där elenergilagring bedöms vara tekniskt och ekonomiskt gångbara och där applikationerna fyller nya behov i kraftsystemet som beror på ökad mängd distribuerad generering (till exempel vindkraft), ökad elenergianvändning beroende på nya belastningsobjekt (elbilar), förändring av distributionsnätens uppbyggnad, med mera.

Bedömning av olika koncept för att gå vidare med pilotprojekt görs så snart det är möjligt med hänsyn till ovan beskrivna konceptuella studier. Prioritering för genomförande görs.

Inom cirka 5 år från nu inleds förverkligande av pilotprojekt. Genomförandetiden för dessa varierar troligen betydligt mellan olika tekniklösningar.

Utvärdering av pilotprojekt görs så snart det är möjligt, med målet att vidare implementering ska kunna ske inom 10 år.

13.2 Uppskalningssteg

Bedömning av uppskalning av olika system måste ske efter hand baserat på tekniska och ekonomiska utvärderingar.

14 Diskussion

Det kan konstateras att inom forskningsvärlden pågår teknikutveckling inom områdena batterier, kondensatorer med mycket stor kapacitans, svänghjul med mera. Eftersom denna rapport endast ger en översiktlig bild av forskning som förekommer kan det konstateras att det finns behov att kontinuerligt följa utvecklingen.

Bedömningen görs att det i Sverige främst finns behov att utvärdera nyttan av elenergilagring i olika applikationer och att identifiera lämpliga metoder för energilagring för de olika applikationerna. Behoven av olika applikationer för elenergilagring bör utredas vidare beträffande nyttovärdering, kostnader, miljöpåverkan, med mera.

15 Slutsatser

Utifrån förutsättningar och behov i Sverige och i Norden bör forsknings- och utvecklingsinsatser göras enligt följande:

Identifiera områden där det finns behov av åtgärder och förbättringar i kraftsystemet. Uppslag till detta:

- Produktionsutjämning i kraftsystemet där behoven ökar på grund av ökad andel generering som är svår att prognostisera (vindkraft).
- Produktionsutjämning i kraftsystemet driven av ekonomisk optimering.
- Utjämning av effektöverföring i elnäten.
- Förbättring av frekvensstabilitet i kraftsystemet där reglerbehoven troligen ökar på grund av nya produktionsanläggningar med liten tröghetstidskonstant.
- Framtagning av alternativ till koncept för distributionsnät där det finns ekonomiska incitament att begränsa lednings/kabelutbyggnad.
- Värdering av risk för instabilitet i kraftsystemet bör göras (transient stabilitet, risk för odämpade elektromekaniska pendlingar och spänningsstabilitet) i dagens och det framtida elnätet.

Utgående från identifierade behov utreds sedan om elenergilagring kan vara användbart för att ge de förbättringar som krävs.

För varje applikationsområde utvärderas sedan olika elenergilagringsalternativ beträffande tekniska möjligheter, miljöpåverkan och ekonomi.

Under de närmsta åren (2 till 4 år framöver) bör konceptuella lösningar tas fram för de olika applikationerna där elenergilagring bedöms vara tekniskt och ekonomiskt gångbara och där applikationerna fyller nya behov i kraftsystemet som beror på ökad mängd distribuerad generering (till exempel vindkraft), ökad elenergianvändning beroende på nya belastningsobjekt (elbilar) och förändring av distributionsnätens uppbyggnad.

För de olika konceptuella lösningarna bör en djup ekonomisk analys genomföras.

Bedömning av olika koncept för att gå vidare med pilotprojekt görs så snart det är möjligt med hänsyn till ovan beskrivna konceptuella studier. Prioritering för genomförande görs.

Inom cirka 5 år från nu inleds förverkligande av pilotprojekt. Genomförandetiden för dessa varierar troligen betydligt mellan olika tekniklösningar.

Utvärdering av pilotprojekt görs så snart det är möjligt, med målet att vidare implementering kan ske inom 10 år.

Angående metoder för energilagring görs följande värderingar:

- Batterilagring: Utvecklingen av Litium-jon batterier är intressant. I dagsläget är det svårt att se energilagring i batterier som ett bra alternativ i applikationer med ofta förekommande omladdningscykler och stora energimängder som omladdas. Den begränsade livslängden och effektbegränsning vid upp- och urladdning är begränsande.
- Energilagring i kondensatorer: ”Super-kondensatorer” med stor effektkapacitet bedöms vara intressanta för applikationer där snabb effektreglering är nödvändig. I samband med utveckling av kondensatorer baserade på kol-nanorör ökas energilagringskapaciteten betydligt och därmed kan detta bli ett alternativ till batterilagring. Vidare är det kombinera batteri- och kondensatorlagring för att få längre livslängd för de laddningsbara batterierna och snabbare effektreglering.
- Energilagring i svänghjul: Energilagringskapaciteten är relativt begränsad medan effektregleringen kan ske snabbt. Därmed kan detta system vara jämförbart med energilager baserat på kondensatorer.
- Energilagring i pumpkraftverk: Detta system är väl lämpat och beprövat för energilagring i tidsskalan ett eller några dygn. I det svenska kraftsystemet finns ännu inte så stort behov för energilagring i denna tidsskala eftersom andelen reglerbar vattenkraft är stor. Dock kan man tänka sig att pumpkraftverk i södra Sverige kan användas för att avlasta kraftnätet i vissa driftlägen och därmed kan behovet av att bygga nya kraftledningar minskas.
- Energilagring med vätgas: Hantering av vätgas i stor skala anges som ett problem.
- Energilagring med luftkomprimering: Denna metod är kombinerad med gasturbinanläggningar där man under perioder med effektöverskott komprimerar luft för att använd senare i gasturbinkraftverk (i stället för kompressor). Denna teknik bör övervägas i framtiden om man planerar att bygga nya gasturbinkraftverk i Sverige. Det bedöms dock att behovet av detta är litet i nuläget.

Referenser

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[4] Persson, S.: "Utredningsrapport om vindkraft – yttrande", Yttrande 02-2002-02960, Energimyndigheten, Elkraft och bostäder, 2002-12-09.

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Aditya, S.K. & Das, D.: "Application of battery energy storage system to load frequency control of an isolated power system", International Journal of Energy Research, vol. 23, no. 3, pp. 247-258, 1999.

A battery energy storage system (BES) can provide fast active power compensation and hence it also can be used to improve the performance of the load frequency control. In this paper, the study is carried out on a single area model representing the whole power system considering generation rate constraint (GRC). An incremental model of BES is proposed and merged into the load frequency control of the power system. Optimum value of integral gain setting is obtained using integral squared technique (ISE). Dynamic responses of the system are presented with and without considering BES facility. Analysis reveals that BES improves the system performance significantly.

Aditya, S. K. & Das, D.: "Load-frequency control of an interconnected hydro-thermal power system with new area control error considering battery energy storage facility", International Journal of Energy Research, vol. 24, no. 6, pp. 525-538, 2000.

This paper deals with load-frequency control of an interconnected hydro-thermal system considering battery energy storage (BES) system. A new area control error (ACEN) based on tie-power deviation, frequency deviation, time error and inadvertent interchange (unscheduled energy transfer) is used for the control of the BES system. Time domain simulations are used to study the performance of the power system and the BES system. Results reveal that BES meets sudden requirements of real power load and is very effective in reducing the peak deviations of frequencies, tie-power, time errors and inadvertent interchange accumulations.

Aditya, S.K. & Das, D.: "Battery energy storage for load frequency control of an interconnected power system", Electric Power Systems Research, vol. 58, no. 3, pp. 179-185, 2001.

This paper deals with load frequency control of an interconnected reheat thermal system considering battery energy storage (BES) system. Area control error (ACE) is used for the control of BES system. Time domain simulations are used to study the performance of the power system and BES system. Results reveal that BES meets sudden requirements of real power load and very effective in reducing the peak deviations of frequency and tie-power and also reduces the steady state values of time error and inadvertent interchange accumulations.

Agbossou, K.; Kolhe, M.; Hamelin, J. & Bose, T.K.: "Performance of a Stand-Alone Renewable Energy System Based on Energy Storage as Hydrogen", IEEE Transaction on Energy Conversion, vol. 19, no. 3, pp. 633-640, 2004.

Electrolytic hydrogen offers a promising alternative for long-term energy storage of renewable energy (RE). A stand-alone RE system based on energy storage as hydrogen has been developed and installed at the Hydrogen Research Institute, and successfully tested for autonomous operation with developed control system and power conditioning devices. The excess energy produced, with respect to the load requirement, has been sent to the electrolyzer for hydrogen production. When energy produced from the RE sources became insufficient, with respect to the load requirement, the stored hydrogen was fed to a fuel cell to produce electricity. The RE system components have substantially different voltage-current characteristics and they are integrated through power conditioning devices on a dc bus for autonomous operation by using a developed control system. The developed control system has been successfully tested for autonomous operation and energy management of the system. The experimental results clearly indicate that a stand-alone RE system based on hydrogen production is safe and reliable.

Ait Hammou, Z. & Lacroix, M.: "A hybrid thermal energy storage system for managing simultaneously solar and electric energy", Energy Conversion and Management, vol. 47, no. 3, pp. 273-288, 2006.

A hybrid thermal energy storage system (HTESS) is proposed for managing simultaneously the storage of heat from solar and electric energy. Solar energy is stored during sunny days and released later during cloudy days or at night, and to smooth power demands, electric energy is stored during off peak periods and later used during peak periods. A heat transfer model of the HTESS is developed and validated with exact solutions and experimental data. Simulations are then performed to examine the effect of various storage materials and of the operating conditions on the thermal behaviour of the HTESS. The results indicate that the consumption of electricity for space heating is minimised when the HTESS consists of a 0.15m thick wall comprising spherical capsules 0.065m in diameter filled with n-octadecane. With such a system, the electric energy consumption during the month of January may be reduced by as much as 30%.

Akuto, K. & Ogata, T.: "Ultra-thin sealed lead-acid batteries", 12th International Telecommunications Energy Conference, INTELEC '90, pp. 451-457, 1990.

The structure and performance of the world's first ultra-thin sealed lead-acid batteries are described. The batteries are 0.65 mm thick; the thinnest ever achieved, and are made possible by a new electrode structure. In a conventional battery, the separator is sandwiched between the positive and negative electrodes. In the new battery structure, however, the positive electrode, electrolyte, and negative electrode are arranged on the same plane. Movement of the battery reaction sites during charge/discharge is parallel to the main surface of the electrode. Consequently, the new battery structure offers significant advantages in regard to life performance. Batteries utilizing this new structure have a long life of over 400 cycles, and good performance of the charge/discharge characteristics. In addition, a variety of different batteries can be manufactured using screen patterns. By using the techniques described above, the thickness of a sealed lead-acid battery can be reduced to less than one seventh of that of a conventional one, without performance degradation.

Aldred, A.S. & Shackshaft, G.: "A frequency-response method for the predetermination of synchronous-machine stability", Proceedings IEE, vol. 107, pt. C, pp. 2-10, 1960.

Aldred, A.S. & Shackshaft, G.: "Frequency-response analysis of the stabilising effect of a synchronous-machine damper", Proceedings IEE, vol. 108, pt. C, pp. 58-63, 1961.

Ali, M. H.; Murata, T. & Tamura, J.: "A Fuzzy Logic-Controlled Superconducting Magnetic Energy Storage for Transient Stability Augmentation", IEEE Transactions on Control Systems Technology, **vol**. 15, no. 1, pp. 144-150, 2007.

This paper presents fuzzy logic-controlled superconducting magnetic energy storage (SMES) to improve the transient stability of an electric power system. In order to see how effective the proposed fuzzy controlled SMES in improving the transient stability is, its performance is compared to that of a conventional proportional-integral (PI) controlled SMES. Furthermore, a comparative study between the fuzzy controlled SMES and fuzzy controlled braking resistor (BR) is carried out. Simulation results show that the performance of fuzzy controlled SMES is better than that of PI controlled SMES. Again, the performance of SMES is better than that of BR. Finally, it can be concluded that the proposed fuzzy controlled SMES provides a very simple and effective means of transient stability enhancement of electric power systems

Allen, D.: "Air Force Electrochemical Power Research and Technology Program for Space Applications", Air Force Wright Aeronautical Labs., Wright-Patterson AFB, September, 1987.

An overview is presented of the existing Air Force electrochemical power, battery, and fuel cell programs for space application. Present thrusts are described along with anticipated technology availability dates. Critical problems to be solved before system applications occur are highlighted. Areas of needed performance improvement of batteries and fuel cells presently used are outlined including target dates for key demonstrations of advanced technology. Anticipated performance and current schedules for present technology programs are reviewed. Programs that support conventional military satellite power systems and special high power applications are reviewed. Battery types include bipolar lead-acid, nickel-cadmium, silver-zinc, nickel-hydrogen, sodium-sulfur, and some candidate advanced couples. Fuel cells for pulsed and transportation power applications are discussed as are some candidate advanced regenerative concepts.

Alwers, E.; Baltisberger, K. & Grabitz, R.: "Asynchronous starting of synchronous machines for pumped storage schemes", Brown Boveri Review, vol. 59, no. 2/3, pp. 60-67, February/March 1972.

Ameri, M.; Hejazi, S.H. & Montaser, K.: "Performance and economic of the thermal energy storage systems to enhance the peaking capacity of the gas turbines", Applied Thermal Engineering, vol. 25, no. 2-3, pp. 241-251, 2005.

There are many gas turbines in Iran favored for coping with the peak electricity demand of the utilities due to their specific properties. However, due to the high ambient temperature in the hot seasons, air mass flow, power output and efficiency of gas turbines decrease considerably. To solve this problem, the inlet air to the gas turbines should be cooled. This paper presents an overview of using the thermal energy storage for combustion turbine inlet air-cooling (TESTIAC) to increase the peaking capacity of it. Several cases of the chilled water and ice storage systems have been studied for the capacity enhancement in Kish power plant. The best case has been selected by economical studies. This study shows that the combustion turbine capacity enhancement will be around 13.6% by using this method. The internal rate of return will be 27.3%. The cost of electricity (COE) is calculated to be 5.36 Cents/kWh which is less than the current price of electricity in Iran on-peak hours.

Anagnostopoulos, J.S. & Papantonis, D.E.: "Simulation and size optimization of a pumped-storage power plant for the recovery of wind-farms rejected energy", Renewable Energy, vol. 33, no. 7, pp. 1685-1694, 2008.

The hybrid wind-hydro power generation appears to be an attractive solution for isolated, autonomous electric grids in order to increase the wind energy penetration and cost-effectiveness. This work presents a numerical methodology for optimum sizing of the various components of a reversible hydraulic system designed to recover the electric energy that is rejected from wind farms due to imposed grid limitations. The algorithm is applied to study a practical case using time variation data of rejected power from a number of wind farms installed in the island of Crete, Greece. The free design parameters of the system include the turbine size, the size and the number of the pumps, the penstock diameter and thickness, and the reservoirs' capacity, whereas some critical financial parameters are also considered. The numerical procedure combines an evaluation algorithm that simulates in detail the plant operation during a 12-month period, and automated optimization software based on evolutionary algorithms. The economic analysis uses dynamic evaluation methods and the attainability of various objectives is examined using single or multi-objective optimizations. In addition, the developed numerical tool is used to perform several parametric studies and sensitivity tests in order to analyse in depth the influence of the most important parameters on the plant operation and economic behaviour. The results showed that a well optimized design may be crucial for the technical and economic viability of the examined system.

Anderson D. & Leach, M.: "Harvesting and redistributing renewable energy: on the role of gas and electricity grids to overcome intermittency through the generation and storage of hydrogen", Energy Policy, vol. 32, no. 14, pp. 1603-1614, 2004.

If intermittent renewable energy technologies such as those based on solar, wind, wave and tidal resources are eventually to supply significant shares of total energy supplies, it is crucial that the energy storage problem is solved. There are several (long-recognised) possibilities ahead including compressed air, pumped storage, further developments in batteries, regenerable fuel cells, 'super-capacitors' and so forth. But one that is being revisited extensively by industry and research establishments is the production and storage of hydrogen from electricity at off-peak times, and in times when there would be a surplus of renewable energy, for reuse in the electricity, gas and transport markets; short-term and even seasonal and longer-term storage is technically feasible with this option. This paper looks at the costs of the option both in the near-term and the long-term relative to the current costs of electricity and natural gas supplies. While the costs of hydrogen would necessarily be greater than those of natural gas (though not disruptively so), when used in conjunction with emerging technologies for decentralised generation and combined heat and power there is scope for appreciable economies in electricity supply. A lot will depend on innovation at the systems level, and on how we operate our electricity and gas grids and regulate our electricity and gas industries. We have also suggested that we now need to experiment more, at the commercial level, and in the laboratories, with the hydrogen option.

Anderson, M.D. & Carr D.S.: "Battery energy storage technologies", Proceedings of the IEEE, vol. 81, no. 3, pp. 475-479, March 1993.

Battery energy storage systems, comprising lead-acid batteries, power conversion systems, and control systems, are discussed. They are used by power generating utilities power distributing utilities, and major power consumers (such as electric furnace foundries). The principal advantages that battery energy storage systems offer generating utilities are described, including load leveling, frequency control, spinning reserve, modular construction, convenient siting, absence of emissions, and investment deferral for new generation and transmission equipment. Power distributing utilities and major power consumers can avoid costly demand changes by discharging their batteries at peak periods and then recharging with lower cost off-peak power (say, at night). Battery energy storage systems are most cost-effective when designed for discharge periods of less than 5 h; other systems (for example, pumped water storage) are better suited for longer discharges. It is estimated that by the year 2000 there will be a potential need for 4000 MW of battery energy storage.

Andrepont J.: "Energy Storage: Not Just R&D Nor Necessarily Expensive", Power Engineering, vol. 110, no. 5, pp. 56, 58, 2006.

Energy storage has long been recognized as a highly desirable and valuable component of electric power systems, whether for utility-scale or small to large distributed generation (DG) systems. Specifically, energy storage can greatly enhance the economics of DG or combined heat and power installations by flattening power supply/demand and better matching electrical and useful thermal outputs. Conventional wisdom has often assumed that energy storage is rather elusive, challenged by technical development and high capital costs. The reality is quite different. Large-scale energy storage applications, specifically as cool thermal energy storage, have been widely employed for years, providing energy storage in both demand-side and supply-side applications and using fully developed performance-guaranteed technology deployed at highly attractive capital costs. Research and demonstration of advanced energy storage technologies is appropriate. But technologies that are already thoroughly proven, commercialized and economically attractive should be preferentially implemented in the marketplace on both the demand and supply sides with the full support of regulators and decision-makers.

Armbruster, T.F.: "Static Converter Starting of Large Pumping Units", Allis-Chalmers Engineering Review, vol. 39, no. 2, pp. 17-21, 1974..

Arrillaga, J.; Bodger, P.S. & Bradley, D.A.: "Power System Harmonics", John Wiley and Sons, New York, 1985.

Arslan, M.A.: "Flywheel geometry design for improved energy storage using finite element analysis", Materials and Design, vol. 29, no. 2, pp. 514-518, 2008.

Flywheels serve as kinetic energy storage and retrieval devices with the ability to deliver high output power at high rotational speeds as being one of the emerging energy storage technologies available today in various stages of development, especially in advanced technological areas, i.e., spacecrafts. Today, most of the research efforts are being spent on improving energy storage capability of flywheels to deliver high power at transfer times, lasting longer than conventional battery powered technologies. Mainly, the performance of a flywheel can be attributed to three factors, i.e., material strength, geometry (cross-section) and rotational speed. While material strength directly determines kinetic energy level that could be produced safely combined (coupled) with rotor speed, this study solely focuses on exploring the effects of flywheel geometry on its energy storage/deliver capability per unit mass, further defined as Specific Energy. Proposed chain of finite element analysis and optimization procedure results show that smart design of flywheel geometry could both have a significant effect on the Specific Energy performance and reduce the operational loads exerted on the shaft/bearings due to reduced mass at high rotational speeds. This paper specifically studies the most common six different geometries (i.e., straight/concave or convex shaped 2D cross-sections) and ranks according to their energy storage performance using the proposed procedure.

Arthur, H.G.: Progress at the Mt. Elbert Pumped Storage Powerplant in Colorado", Water Power, vol. 26, no. 6, pp. 197-204, June 1974.

Atkin, G.: "Energy storage: cost still dominate choice", Energy Storage, pp. 13-17, July/August, 1980.

Babarit, A.; Ben Ahmed, H.; Clement, A.H.; Debusschere, V.; Duclos, G.; Multon, B. & Robin, G.: "Simulation of electricity supply of an Atlantic island by offshore wind turbines and wave energy converters associated with a medium scale local energy storage", Renewable Energy, vol. 31, no. 2, pp. 153-160, 2006.

The problem of sizing an electricity storage for a 5000 inhabitants island supplied by both marine renewables (offshore wind and waves) and the mainland grid is addressed by a case study based on a full year resource and consumption data. Generators, transmission lines and battery storage are accounted for through basic simplified models while the focus is put on electricity import/export budget. Self-sufficiency does not seem a reasonable goal to pursue, but partial autonomy provided by renewable sources and a medium size storage would probably be profitable to the island community.

Badr, M.A.; Soliman, S.A. & Zahran, S.A.: "A novel technique for direct online starting of pump storage synchronous machines", in Reichert, K. & Neubauer, R.E. (editors): Proceedings. International Conference on the Evolution and Modern Aspects of Synchronous Machines, Zurich, 27-29 August 1991, vol. 1, pp. 189-193, Institute of Electrical Machines, Zurich, 1991.

Huge synchronous generators operating in pumped storage power stations need to be directly connected online for motor operation during periods of low power demand. Due to their excessive inertia constant and low starting torque, the start -up time becomes considerable. This imposes problems of voltage dips and thermal stresses. The low starting torque is attributed to the uncontrolled small rotor resistance. The authors present a novel approach to the solution of this problem through the adoption of the principle of slip frequency excitation. Here, the synchronous generator, being doubly excited, has a more flexible rotor circuit. The two field windings can be either slip frequency excited or connected to optimum starting resistors. The improvement in the starting -up process is verified through a rigorous transient analysis.

Bagshaw, N.E.: "Batteries on Ships", John Wiley & Sons, New York, 1982.

Baker, J.N. & Collinson, A.: "Electrical energy storage at the turn of the Millennium", Power Engineering Journal, vol. 13, no. 3, pp. 107-112, 1999.

Electrical energy storage is currently enjoying a considerable resurgence of interest, aided both by advances in the systems technologies themselves and also by fundamental changes in electricity markets, allowing the benefits of storage to be move clearly identified. This article, which introduces a special feature on "electrical energy storage", reviews the state of the art and developments into the next Century, existing and potential applications, market potential for utilities and users and the increasing attention from Government agencies, manufacturing industry and research organisations. It concludes that the forthcoming challenge is for the various systems to prove both their technical and their commercial viability.

Ball, G.J.; Corey, G. & Norris, B.L.: "Government, industry, and utility development and evaluation of a modular utility battery energy storage system", IEEE Transaction on Energy Conversion, vol. 10, no. 3, pp. 549-554, 1995.

A prototype 250 kVA modular battery energy storage system was developed and tested for utility peak-shaving applications-in a cooperative Department of Energy, industry, and utility project. The system consists of battery- and converter-integrated modules with AC terminals. Data on the system's energy capacity, power quality, power factor, auxiliary power, thermal regulation, speed of response, and islanding and other protective measures are presented. A simple method of identifying the presence of a defective battery was revealed during the test period.

Bard, A.J. & Faulkner, L.R.: "Electrochemical Methods – Fundamental and Applications", John Wiley & Sons, New York, 1980.

Barsoukov, E.; Kim, J.H.; Yoon, C.O. & Lee, H.: "Universal battery parameterization to yield a non-linear equivalent circuit valid for battery simulation at arbitrary load", Journal of Power Sources, vol. 83, no. 1-2, pp. 61-70, 1999.

A method of numerical representation for electrical storage cells based on measurement of wide frequency range impedance spectra at a number of different states of charge and measurement of the depth-of-discharge dependence of equilibrium voltage are developed. Applicability of this method to batteries with various chemistries and sizes are established by comparing numerical prediction to experiment. The model represents all tested batteries with accuracy (less than 1% in average deviation) in processes ranging from time constants of 1 ms to 10 h and from current densities of C/10 to 3C. The method includes the fitting of impedance spectra to physically relevant static linear transmission-line model and the use of parameters determined at different discharge levels to create a non-linear dynamic model. Formalization of the model as a non-linear equivalent circuit enables its direct application as a part of any electric device in digital circuit simulators like SPICE.

Barth, S.: "Felsmechanische Probleme beim Entwurf der Kaverne des Pumpspeicherwerkes Waldeck II", Bautechnik, vol. 49, pp. 73-83, 1972.

Barton, J.P. & Infield, D.G.: "Energy Storage and Its Use With Intermittent Renewable Energy", IEEE Transaction on Energy Conversion, vol. 19, no. 2, pp. 441-448, 2004.

A simple probabilistic method has been developed to predict the ability of energy storage to increase the penetration of intermittent embedded renewable generation (ERG) on weak electricity grids and to enhance the value of the electricity generated by time-shifting delivery to the network. This paper focuses on the connection of wind generators at locations where the level of ERG would be limited by the voltage rise. Short-term storage, covering less than 1 h, offers only a small increase in the amount of electricity that can be absorbed by the network. Storage over periods of up to one day delivers greater energy benefits, but is significantly more expensive. Different feasible electricity storage technologies are compared for their operational suitability over different time scales. The value of storage in relation to power rating and energy capacity has been investigated so as to facilitate appropriate sizing.

Baudry, P.: "Electro thermal modelling of polymer lithium batteries for starting period and pulse power", Journal of Power Sources, vol. 54, pp. 393-396, 1995.

Baumann, P.D.: "Energy Conservation and Environmental Benefits that May Be Realized from Superconducting Magnetic Energy Storage", IEEE Trans. on Energy Conversion, vol. 7, no. 2, pp. 253-259, June, 1992.£

Beck, J.W.; Carroll, D.P.; Gareis, G.E.; Krause, P.C. & Ong, C.M.: "A computer study of battery energy storage and power conversion equipment operation", IEEE Transactions on Power Apparatus and Systems, vol. PAS-95, no. 4, part-1, pp. 1064-1072, 1976.

This paper presents and discusses results from a computer simulation of a battery energy storage/converter system connected to a representative utility substation. Switching of load, voltage waveforms, voltage levels, fault conditions, and power flow reversal are investigated for both line- and forced-cornmutated converters in the application. The interactions among the battery, the converter and its controls, and the substation are discussed. The investigations have pointed out areas in which further consideration must be given to component selection for the battery/utility interface equipment, for example, dc reactor sizing, harmonic filtering, power factor control, thyristor firing control, and dc current interruption.

Berndt, D.: "Maintenance-Free Batteries. Lead-Acid, Nickel/Cadmium, Nickel/Hydride, A Handbook of Battery Technology", Research Studies Press, John Wiley & Sons, Chichester, 1993.

Berndt, D.: "Maintenance-Free Batteries – Lead-Acid, Nickel/Cadmium, Nickel/Metal Hydride – A Handbook of Battery Technology", Second Edition, Research Studies Press, Taunton, Sommerset, England & John Wiley & Sons, New York, Chichester Toronto, Brisbane Singapore, 1997.

Berndt, D.; Bräutigam, R. & Teutsch, U.: "Temperature compensation of float voltage", Proceedings of the 17th International Telecommunications Energy Conference (Intelec), The Hague, pp. 1–12, 1995.

Berndt, D. & Teutsch, U.: Journal of the Electrotechnical Society, vol. 143, p. 790, 1996.

Bernhoff, H.: "Översikt av elektrisk energilagring", Slutrapport från P13814-1, EFA-02/2, 2002.

> Möjligheterna till och villkoren för elektrisk energilagring, s.k. ellagring, i det svenska elnätet har utvärderats i ett scenario av ökad förnybar elkraft. Av de tekniker som har studerats förefaller pumpkraft och svänghjul ha den största potentialen. Vatten- kraften i norra Sverige bör anpassas till dess nya roll som energilager för förnybar produktion. I södra Sverige skulle möjligen ett eller flera pumpkraftverk i anslutning till Vänern eller Vättern kunna vara ett alternativ till ökad transmission från Norrland. Svänghjul har den största potentialen att fungera som energilager i samband med utbyggnad av förnybar elkraft både vad gäller effekt- och energi kapacitet.

Bhargava, B. & Dishaw, G.: "Application of an energy source power system stabilizer on the 10 MW battery energy storage system at Chino substation", IEEE Transactions on Power Systems, vol. 13, no. 1, pp. 145-151, 1998.

> Southern California Edison (SCE) installed a 10 MW battery energy storage system (BESS) at its Chino substation facility in 1988. The BESS facility has been in operation for six years and has been used for load leveling and peaking functions. The BESS power conversion system was built with the then state of the art technology and has a very fast response rate when changing power output of the batteries. SCE installed an energy source power system stabilizer (ESPSS) to test the concept of providing damping of power system swings using the ESPSS. The ESPSS basically modulates the power output/input of the energy storage batteries to respond to system frequency deviations caused by power system oscillations. The ESPSS differs from a conventional power system stabilizer. It is designed to change the power output of the power source rather than the voltage or the reactive power output. While installing the ESPSS several upgrades to the BESS were made to improve reliability. Installation of the ESPSS on the battery enables SCE to test the concept of system stabilization using power source output modulation instead of reactive power modulation. The energy storage batteries provide an easy test bed for conducting field tests and response of the ESPSS to system disturbances. This paper discusses the BESS, the ESPSS and presents recorded results from system disturbance monitoring and field tests conducted on the ESPSS and the batteries.

Bilodeau, A. & Agbossou, K.: "Control analysis of renewable energy system with hydrogen storage for residential applications", Journal of Power Sources, vol. 162, no. 2, pp. 757-764, 2006.

> The combination of an electrolyzer and a fuel cell can provide peak power control in a decentralized/distributed power system. The electrolyzer produces hydrogen and oxygen from off-peak electricity generated by the renewable energy sources (wind turbine and photovoltaic array), for later use in the fuel cell to produce on-peak electricity. An issue related to this system is the control of the hydrogen loop (electrolyzer, tank, fuel cell). A number of control algorithms were developed to decide when to produce hydrogen and when to convert it back to electricity, most of them assuming that the electrolyzer and the fuel cell run alternatively to provide nominal power (full power). This paper presents a complete model of a stand-alone renewable energy system with hydrogen storage controlled by a dynamic fuzzy logic controller (FLC). In this system, batteries are used as

energy buffers and for short time storage. To study the behavior of such a system, a complete model is developed by integrating the individual sub-models of the fuel cell, the electrolyzer, the power conditioning units, the hydrogen storage system, and the batteries. An analysis of the performances of the dynamic fuzzy logic controller is then presented. This model is useful for building efficient peak power control.

Blankinship, S.: "Compressed air energy storage development gets funding", Power Engineering, vol. 106, no. 6, pp. 18, 2002.

Compared to peaking gas turbines, CAES (compressed air energy storage) can provide 80% efficiency in power production mode, 60% lower emissions, and 2 to 3 times faster ramp rates. Ridge Energy Storage and Grid Services has announced an agreement with El Paso Corp. subsidiary EP Energy Finance for $15 million of capital to develop compressed air energy storage projects.

Blarke, M.B. & Lund, H.: "The effectiveness of storage and relocation options in renewable energy systems", Renewable Energy, vol. 33, no. 7, pp. 1499-1507, 2008.

Across the world, energy planners and transmission system operators are faced with decisions on how to deal with challenges associated with high penetration levels of intermittent energy resources and combined heat and power (CHP). At the same time, distributed plant operators are eager to reduce uncertainties related to fuel and electricity price fluctuations. These interests meet-up for options in distributed supply that introduces the principle of storage and relocation, typically by integrating heat pumps (HP) or electric boilers (EBs) into the operational strategies of existing CHP plants. This paper introduces the principle of storage and relocation by energy system design, and proposes for the storage and relocation potential of a technology option to be found by comparing options by their storage and relocation coefficient Rc, defined as the statistical correlation between net electricity exchange between plant and grid, and the electricity demand minus intermittent renewable electricity production. Detailed operational analyses made for various CHP options within the West Danish energy system, point to the concepts of CHP-HP and CHP-HP cold storage for effectively increasing energy system flexibility. For CHP-HP cold storage, Rc increases from 0.518 to 0.547, while the plant's fuel efficiency increases from 92.0% to 97.2%. These findings are discussed within frameworks of renewable energy systems, suggesting principles for 1st, 2nd, and 3rd generation system designs.

Blind, H.: "Planning of Pumped Storage Plants", Water Power, vol. 19, June-July, 1967.

Bockris, J. O'M & Drazic, D.M.: "Electro-Chemical Science", Taylor & Francis, London, 1972.

Bode, H.: "Lead Acid Batteries", John Wiley & Sons New York, 1977.

Bojtor, L. & Paal, E.: "Static starter for gas turboset and pumped storage hydropower plant", Proceedings of the Symposium on Power Electronics Electrical Drives Advanced Machines Power Quality (SPEEDAM), Sorrento, 3-5 June 1998, vol. 1, pp. P4/29-32, University Federico II, Napoli 1998.

The paper introduces a modern static frequency converter family developed by Ganz Ansaldo mainly for start -up purposes of gas turboset and pumped storage hydropower plants. The main circuit configuration and the technical data of the static starter equipment are described. The control strategies and the architecture of the microcomputer control system are discussed in detail. Field experiences are also presented.

Bolund, B.; Bernhoff, H. & Leijon, M.: "Flywheel energy and power storage systems", Renewable and Sustainable Energy Reviews, vol. 11, no. 2, pp. 235-258, 2007.

For ages flywheels have been used to achieve smooth operation of machines. The early models where purely mechanical consisting of only a stone wheel attached to an axle. Nowadays flywheels are complex constructions where energy is stored mechanically and transferred to and from the flywheel by an integrated motor/generator. The stone wheel has been replaced by a steel or composite rotor and magnetic bearings have been introduced. Today flywheels are used as supplementary UPS storage at several industries world over. Future applications span a wide range including electric vehicles, intermediate storage for renewable energy generation and direct grid applications from power quality issues to offering an alternative to strengthening transmission. One of the key issues for viable flywheel construction is a high overall efficiency, hence a reduction of the total losses. By increasing the voltage, current losses are decreased and otherwise necessary transformer steps become redundant. So far flywheels over 10kV have not been constructed, mainly due to isolation problems associated with high voltage, but also because of limitations in the power electronics. Recent progress in semi-conductor technology enables faster switching and lower costs. The predominant part of prior studies has been directed towards optimising mechanical issues whereas the electro technical part now seems to show great potential for improvement. An overview of flywheel technology and previous projects are presented and moreover a 200 kW flywheel using high voltage technology is simulated.

Bonner, J.A.; Hurst, W.M.; Rocamora, R.G. Dudley, R.F.; Sharp, M.R. & Twiss, J.A.: "Selecting ratings for capacitors and reactors in applications involving multiple single-tuned filters", IEEE Transactions on Power Delivery, vol. 10, pp. 547-555, 1995.

Boost, M. & Ziogas, P. D.: "Towards a zero output impedance UPS system", in PESC Record - IEEE Power Electronics Specialists Conference, pp. 497, 1987.

The types of loads requiring clean uninterruptible power has expanded substantially during recent years. Since a number of these loads are unbalanced and/or nonlinear, today's typical uninterruptible power supply can no longer guarantee clean power for many of these loads without additives and/or interfacing techniques. The authors categorize these loads, analyze their effects, and survey present, partial solutions. A topology is presented for a low-impedance 3-phase high power inverter stage that alleviates these difficulties.

Boretz, J.F.: "Space power alternatives for laser radar sensor system", IEEE Aerospace and Electronic Systems Magazine, vol. 5, pt. 1, no. 3, pp. 3-8, March, 1990.

Seven candidate power systems for the sensor of a space-based laser radar system are identified, and their performance and operating characteristics are briefly described. The systems are the NiCd battery, NiH//2 battery, NaS battery, LiSO//2Cl//2 battery, LiAl-FeS//2 battery, H//2/O//2 fuel cell, and an inertial flywheel generator. The systems encompass a current or projected specific energy range of from 15.0 to 100 Wh/lb. To arrive at a meaningful basis for comparison and to aid in system selection, a figure-of-merit (FOM) was established. Because the FOM is somewhat qualitative in content, scoring weighting factors were utilized to further quantify the results. The NiH//2 battery and the NaS battery received the highest FOM rankings. Following next in order were the H//2/O//2 fuel cell and the inertial flywheel generator. The NiCd and lithium thermal batteries received the lowest ratings. These results are of a preliminary nature. Extension of these analyses to include reliability and cost factors is recommended.

Bose, B.; Canay, M. & Simond, J.-J.: "Frequency Starting in Pumped Storage Plants: Possibilities and Optimization", Brown Boveri Review, vol. 70, no. 7-8, pp. 295-302, July-August 1983.

Boyes J.D.: "Overview of energy storage applications", IEEE Power Engineering Society Summer Meeting, vol. 3, pp. 1514-1516, 2000.

Sandia National Laboratories has been studying energy storage systems since the late 1970s. Sandia's role, as a Department of Energy funded program, is to look ahead at emerging technologies, perform early R&D and identify applications for energy storage systems that offer significant benefit to the nation's electricity providers and users. In order to identify applications of energy storage, a two-phase Opportunities Analysis was conceptualized in FY94. The group of industry experts participating in the study reviewed the requirements for each of the applications identified in Phase I, modified application names, and combined some applications to better reflect the nature of the electricity industry today. Participants of the Phase II analysis used the perceived need for the application across the nation, and the potential technical and economic benefits for utilities as criteria to evaluate the applications.

Brad, R.: "Energy Storage", Power, vol. 150, no. 8, pp. 76-77, 2006.

As load growth on U.S. transmission and distribution grids continues to shrink reserve margins nationwide, utilities are looking for new ways to meet demand peaks. Until recently, the most elegant (no moving parts) option at utility-scale levels - adding a sizable storage battery to a substation - remained just out of reach because available batteries weren't able to meet the hours of discharge on a daily basis. Welcome to the future of bulk electricity storage. Earlier this year, American Electric Power (AEP) installed a 1.2-MW sodium sulfur (NaS) battery and accompanying inverter at the Charleston Substation of its subsidiary, Appalachian Power. The Charleston Substation was chosen to host the installation for several reasons related to economics, service reliability, and local load growth. The main function of the system is to supply up to 7.2 MWh of electrical energy on demand for peak-shaving purposes.

Brauner, G.; Pesch, H. & Wahi, A.: "Load management and dynamic stability improvement in industrial networks by battery energy storage plant", 10th International Conference on Electricity Distribution, CIRED, pp. 397-401, vol. 5, 1989.

Battery storage plants (BSP) are either already in operation or under planning in many utility and industrial companies. The main fields of their application are the improvement of frequency control in island networks, voltage maintenance in radial feeder networks, and load control. In industrial networks with a large component of motoric load, BSP can help in the fast balancing of active and reactive power after network separation. The authors show that problems of reacceleration of motors and damping of power oscillations of generators can be coped with equally well.

Bray, A.N.G. & Frost, A.C.H.: "The Selection of Pumped Storage Plant with particular Reference to Tumut 3 Project", The Journal of the Institution of Engineers, Australia, September 1967.

Brown, P.G.: "Reduced Voltage Starting Performance of Synchronous Condensers and Pumped Hydro Units", Paper PG 75643-7 presented at the Joint Power Generation Conference, 1975.

Brown, P.G.: "Reduced Voltage Starting Performance of Synchronous Condensers and Pumped Hydro Units", IEEE Transactions on Power Apparatus and Systems, no. 2, pp. 505-511, March/April 1976.

Brown, P.G.: "Reduced Voltage Starting Performance of Synchronous Condensers and Pumped Hydro Units", IEEE Transactions on Power Apparatus and Systems, no. 2, pp. 643-647, March/April 1976.

Brown, P.G. & Otte, G.W.: "Electrical Design Considerations in Pumped Storage Hydro Power Plants", Paper IEEE 63-1227, IEEE Transactions on Power Apparatus and Systems, PAS-82, Special Supplement, pp. 625-641, 1963.

Brüderlin, R.: "Zum Frequenzanlauf synchroner Maschinen", Elektrotechnische Zeitschrift, vol. 45, no. 46, pp. 1239-1240, 13 November, 1924.

Buckles, W. & Hassenzahl, W.V.: "Superconducting magnetic energy storage", IEEE Power Engineering Review, vol. 20, no. 5, pp. 16-20, 2000.

Superconducting magnetic energy storage (SMES) is an energy storage technology that stores energy in the form of DC electricity that is the source of a DC magnetic field. The conductor for carrying the current operates at cryogenic temperatures where it is a superconductor and thus has virtually no resistive losses as it produces the magnetic field. The overall technology of cryogenics and superconductivity today is such that the components of a SMES device are defined and can be constructed. The integrated unit appears to be feasible for some utility applications at a cost that is competitive with other technologies. SMES is the only technology based on superconductivity that is applicable to the electric utilities and is commercially available today. In addition to today's power quality application, the historical development of SMES starting with the concept of very large plants that would store hundreds of megawatt hours of energy and were intended for diurnal load leveling are described.

Bumby, J.R.; Clarke, P.H. & Forster, I.: "Computer modelling of the automotive energy requirements for internal combustion engine and battery electric-powered vehicle", IEE Proceedings, vol. 132, pt. A, no. 5, pp. 265-279, September 1985.

Butler, P.C.; Cole, J.F. & Taylor, P.A.: "Test profiles for stationary energy-storage applications", Journal of Power Sources, vol. 78, no. 1-2, pp. 176-181, 1999.

Evaluation of battery and other energy-storage technologies for stationary uses is progressing rapidly toward application-specific testing. This testing uses computer-based data acquisition and control equipment, active electronic loads and power supplies, and customized software, to enable sophisticated test regimes which simulate actual use conditions. These simulated-use tests provide more accurate performance and life evaluations than simple constant resistance or current testing regimes. Several organizations are cooperating to develop simulated-use tests for utility-scale storage systems, especially battery energy-storage systems (BESSs). Some of the tests use stepped constant-power charge and discharge regimes to simulate conditions created by electric utility applications such as frequency regulation (FR) and spinning reserve (SR). Other test profiles under development simulate conditions for the energy-storage component of remote-area power supplies (RAPSs), which include renewable and/or fossil-fuelled generators. Various RAPS applications have unique sets of service conditions that require specialized test profiles. Almost all RAPS tests and many tests that represent other stationary applications need, however, to simulate significant time periods that storage devices operate at low-to-medium states-of-charge without full recharge. Consideration of these and similar issues in simulated-use test regimes is necessary to predict effectively the responses of the various types of batteries in specific stationary applications. This paper describes existing and evolving stationary applications for energy-storage technologies and test regimes, which are designed to simulate them. The paper also discusses efforts to develop international testing standards.

Canady, C.R. & Drake, J.H.: "Operation of Synchronous Condensers on the Southern California Edison Company System", AIEE Transactions, vol. 71 (Power Apparatus and Systems), pp. 1051-1058, 1952.

Canay, M.: "Der Frequenz-Anlauf von Synchronmaschinen", Archiv für Elekrotecchnik, vol. 44, no. 4, pp. 251-270, 1959.

Canay, M.: "Anlaufverfahren bei Synchronmaschinen", Brown Boveri Mitteilungen, pp. 618-629, 1967.

Canay, M.: "Methods of starting synchronous machines", Brown Boveri Review, vol. 54, no. 9, pp. 618-629, September 1967.

Canay, M.: "Graphische Behandlung des Asynchronlaufes von Synchronmaschinen mit lamellierten und massiven Polen", ETZ-A, pp. 123-129, 1967.

Canay, M.: "Equivalent circuits of synchronous machines for calculating quantities of the rotor during transient processes and asynchronous starting Part II: Salient Pole Machines ", Brown Boveri Review, vol. 57, no. 3, pp. 134-145, March 1970.

Canay, M.: "Asynchronous starting of synchronous machines with or without rectifiers in the field circuit", Proceedings IEE, vol. 119, no. 12, pp. 1701-1708, December 1972.$

Canay, M.: "Asynchronous starting of synchronous machines with or without rectifiers in the field circuit", Proceedings IEE, vol. 120, no. 11, pp. 1414-1416, November 1973.

Canay, M.: "Asynchronous Starting of a 230 MVA Synchronous Machine in 'Vianden 10' Pumped Storage Station", Brown Boveri Review, vol. 61, no. 7, pp. 313-318, July 1974.

Canay, M.: "Partial Frequency Starting in Pumped Storage Stations", Brown Boveri Review, vol. 61, no. 7, pp. 319-326, July 1974.

Carbone, R.; Mangoni, V.; Mirone, C.; Paterno, P.; Testa, A. (Naples University): "Interharmonic distortion in the static starting-up system of a hydroelectric pumped- storage power station", Proceedings of 7th International Conference on Harmonics and Quality of Power (ICHQP), Las Vegas, 16-18 October 1996, pp.299-306, University of Nevada, Las Vegas, 1996.

> The results of several measurements and numerical simulations on the static start -up system of a high-power Italian hydroelectric power station are reported and analysed. Their main outcome is that, in some working conditions, surprisingly high values characterise the low frequency interharmonic components on the DC-side current of the two-power converter scheme utilized for the plant's start -up system; also amplitudes higher than those of the main characteristic harmonics are reached. Considerations on the influence of the main static start -up system parameters on the distortion and possible explanations of the interharmonic high levels are also reported.

Carr, D.S.: "Ten-megawatt load-levelling lead/acid battery project", Journal of Power Sources, vol. 23, no. 1-3, pp. 183-192, 1988.

> To demonstrate the economic and operational feasibility of using lead/ acid batteries for load management by electric utilities, a 10 MW/40 MW h battery energy storage plant is being constructed at the 12 kV substation of Southern California Edison Company in Chino, California. This U.S. $13 million project is a cooperative effort by Edison, Electric Power Research Institute, and International Lead Zinc Research Organization, Inc. The design, construction and operation of this plant are presented. The Chino facility is scheduled to begin load-levelling duties in April, 1988. Several related projects in other areas of the world are also described briefly.

Chang, M.-Y.; Ou, R.-S. & Tzou, Y.-Y.: "DSP-based fuzzy control of bilateral IGBT PWM DC-to-AC and DC-to-DC converters for battery energy storage system", Proceedings of the International IEEE Conference on Industrial Electronics, Control, and Instrumentation, IECON'93, vol. 2,, pp. 1117-1122, 1993.

> This paper presents the full digital control of a bilateral pulsewidth modulated (PWM) DC/AC and DC/DC converter for a battery energy storage system (BESS) using a digital signal processor (DSP). The concerned BESS consists of a switched-mode current-controlled rectifier (SCR) for power flow control and a bilateral buck/boost converter (BBC) for battery charging control. The gating signals for the SCR and BBC are determined at every sampling instant by a DSP-based fuzzy controller using a set of instantaneous feedback signals. The experimental results of a 0.75 kW prototype system are shown to verify the proposed control scheme.

Chatelain, J.: "Motor-generators for pumping power stations", Electra, no. 14, pp. 17-20, 1970.

Chatelain, J. & Simond, J.J.: "Back-to-Back Starting of High Power Synchronous Motors for Storage Schemes", Report 11-02, 25th CIGRE Session, Paris, August 21-29, 1974.

Chen Chao & Grantham, C.: "Design Consideration of a High-Temperature Superconducting Magnet for Energy Storage in an Active Power Filter", IEEE Transactions on Applied Superconductivity, vol. 16, no. 2, pp. 612-615, 2006.

Installing active power filters (sometimes called active harmonic filters or line conditioners) in an electric power network can improve the quality of electricity supply. A shunt active power filter, with a current-source PWM inverter and a conventional copper inductor as its energy storage, has a significant power loss. The power loss in this copper inductor can be substantially reduced by replacing the inductor with a high-temperature superconducting (HTS) magnet. Several solenoid design alternatives using silver-sheathed BSCCO-2223 tape have been made for the HTS magnet that has an inductance of 0.5 H for this application. A liquid-nitrogen-cooled HTS magnet has been built and tested for use in an active power filter. The loss-reduction effect of using the HTS magnet with the current-source active power filter has been investigated experimentally, and the results are compared with those when using a conventional copper inductor. Practical issues such as air-core design versus iron-core design and using liquid-nitrogen cooling or a cryocooling are analyzed and discussed.

Chiang, J.-C.; Wu, C.-J. & Yen, S.-S. (Dept. of Electrical Engineering, National Taiwan Institute of Technology,Taipei): "Mitigation of Harmonic Disturbance at Pumped Storage Power Station with Static Frequency Converter", IEEE Transactions on Energy Conversion, vol. 12, no. 3, pp. 232-240, September 1997.

This paper investigates the harmonic distortion problem and mitigation method at the Mingtan pumped storage power station in Taiwan, where six 300 MVA synchronous generator/motors are started by a static frequency converter (SFC) before the pumping stage. Since the SFC uses a 6-pulse rectifier technique, a large amount of harmonic currents are produced during the starting period. The harmonic distortion level at each bus of the power plant was very high. Especially, the total harmonic distortion (THD) of current at the lighting feeder reached up to 184%, so that power fuses burned out. At first a 5 mH reactor was inserted in the SFC feeder and a 5th order and high pass filter was installed. However, the harmonic distortion levels were still too high, but there is no space for additional higher-order filters. Finally, the SFC is fed with an individual transformer and the harmonic disturbance problem is avoided. This paper also gives computer simulations to investigate the harmonic distortion problems and verify the mitigation methods.

Chiang, S.J.; Huang, S.C. & Liaw, C.M.: "Three-phase multifunctional battery energy storage system", IEE Proceedings - Electric Power Applications, vol. 142, no. 4, pp. 275-284, 1995.

A three-phase multifunctional battery energy storage system (BESS) is designed and implemented. When the utility power is in normal condition, the proposed BESS can be arranged to shave the peak load or charge the battery bank. In either case, since the load unbalanced, harmonic and reactive powers can be compensated through the proposed active power filter control, the power factor is maintained at nearly unity and the line currents drawn from the utility are balanced and sinusoidal with very low distortion. As the utility power failure occurs, the proposed BESS can immediately supply uninterruptible power to the loads. In this case, an instantaneous control technique is developed to yield good three-phase voltage waveforms. The determination of the reactive components, the dynamic modelling, and the design of controllers for the proposed BESS are introduced. A 5 kVA prototype system is implemented and some experimental results are provided to demonstrate the functions and performance of the proposed BESS. Finally, the strategies for scaling up the power capacity of the proposed BESS are discussed.

Chiang, S.J.; Liaw, C.M.; Chang, W.C. & Chang, W.Y.: "Multi-module parallel small battery energy storage system", IEEE Transaction on Energy Conversion, vol. 11, no. 1, pp. 146-154, 1996.

This paper presents a multi-module parallel single-phase battery energy storage system (BESS). The single module BESS to be paralleled consists of only a full-bridge power converter. When the utility is in normal condition, the BESS serves as a power conditioner as well as an active power filter. It can be arranged to charge the battery bank or to share daily peak load. In any case, the current supplied by the electric utility can be maintained sinusoidal and almost in phase with voltage. When a utility power failure occurs, the BESS functions as an inverter to supply uninterruptible power to the load. With the good current sharing feature possessed by this BESS, a central power distribution control scheme with smooth current transfer characteristic is proposed to control the parallel operation of the multi-module BESS. The current sharing of each BESS module can be programmed according to its rating and the load condition. Designs of the power cir-

cuit and the central power distribution control scheme are described detailedly in this paper. The effectiveness and performance of the proposed parallel BESS are demonstrated by some experimental results.

Chiang, S.J.; Chang, K.T. & Yen, C.Y.: "Residential photovoltaic energy storage system", IEEE Transactions on Industrial Electronics, vol. 45, no. 3, pp. 385-394, 1998.

This paper introduces a residential photovoltaic (PV) energy storage system, in which the PV power is controlled by a DC-DC power converter and transferred to a small battery energy storage system (BESS). For managing the power, a pattern of daily operation considering the load characteristic of the homeowner, the generation characteristic of the PV power, and the power-leveling demand of the electric utility is prescribed. The system looks up the pattern to select the operation mode, so that powers from the PV array, the batteries and the utility are utilized in a cost-effective manner. As for the control of the system, a novel control technique for the maximum power-point tracking (MPPT) of the PV array is proposed, in which the state-averaged model of the DC-DC power converter, including the dynamic model of the PV array, is derived. Accordingly, a high-performance discrete MPPT controller that tracks the maximum power point with zero-slope regulation and current-mode control is presented. With proposed arrangements on the control of the BESS and the current-to-power scaling factor setting, the DC-DC power converter is capable of combining with the BESS for performing the functions of power conditioning and active power filtering. An experimental 600 W system is implemented, and some simulation and experimental results are provided to demonstrate the effectiveness of the proposed system.

Christakis, D. & Psofogiannakis, M.: "Reduction of electricity cost by pump-storage unit in Crete island", Proceedings of the 31st Universities Power Engineering Conference (UPEC96), Iraklio,18-20 September 1996, vol. 1, pp. 330-333, Technological Education Institute, Iraklio, 1996.

The electricity production system of the island of Crete is far from optimum; a considerable part of the energy produced originates from inefficient units burning expensive diesel oil. Due to large seasonal and daily variations of power demand, future expansion of the production system cannot be realised by cost effective base load units, as these should stop and start on a daily basis. In this paper, the effect of the addition of pump storage systems (PSSs) on the electricity production cost is examined. The PSSs pump water from a low-level reservoir by using power produced during the night from the base load units of the system, which burn inexpensive heavy fuel oil. Water from the high level reservoir is exploited by the PSS to produce low cost energy during the peak demand hours, thus replacing operation of diesel oil burning units.

Concordia, C.: "Synchronous machine damping torque at low speeds", AIEE Transactions, vol. 69, pp. 1550-1555, 1950.

Concordia, C.: "Synchronous machine damping and synchronizing torques", AIEE Transactions, vol. 70, pp. 731-737, 1951.

Concordia, C.: "Synchronous Machines, Theory and Performance", John Wiley & Sons, New York, 1951.

Concordia, C. & Kron, G.: "Damping and synchronising torques of power selsyns", AIEE Transactions, vol. 64, pp. 366-371, 1945.

Concordia, C.; Crary, S.B.; Kilbourne, C.E. & Weygandt, C.N. Jr.: "Synchronous starting of generator and motor", AIEE Transactions (Electrical Engineering), vol. 64, pp. 629-634, September 1945.

Concordia, C.; Brown, P.G.; Miller, W.J. & Wuosmaa, L.: "Synchronous Starting of Motor from Generator of Small Capacity", IEEE Transaction on Power Apparatus and Systems, vol. PAS-86, no. 10, pp. 1215-1226, October 1967.

Conte, M.; Prosini, P.P. & Passerini, S.: "Overview of energy/hydrogen storage: state-of-the-art of the technologies and prospects for nanomaterials", Materials Science and Engineering B, vol. 108, no. 1-2, pp. 2-8, 2004.

A sustainable energy economy will be demanding primary energy sources, preferably renewable and mainly domestically available, using energy carriers, such as hydrogen and electricity, able to solve environmental problems and to assure adequate energy security. Instrumental to such goals will be the research and development of storage systems with performance characteristics compatible with major application requirements. Lithium or nickel are replacing lead in batteries, in order to better meet the extremely varying technical and economical requirements in fast growing conventional and new applications. Moreover, few technologies now permit to store hydrogen by modifying its physical state in gaseous or liquid form. The variety of hydrogen needs in the energy systems and in the vehicular sector is justifying the effort on solid state (metal hydrides and carbon nanostructures) or chemical systems (chemical hydrides). In this overview, emphasis is given to the major achievements in the field of electrical energy and hydrogen storage, in relation to the technological goals, which have been proposed in the major public research and collaborative programs throughout the world.

Converse, A.O.: "The impact of large-scale energy storage requirements on the choice between electricity and hydrogen as the major energy carrier in a non-fossil renewables-only scenario", Energy Policy, vol. 34, no. 18, pp. 3374-3376, 2006.

The need for large-scale storage, when the energy source is subject to periods of low-energy generation, as it would be in a direct solar or wind energy system, could be the factor which justifies the choice of hydrogen, rather than electricity, as the principal energy carrier. It could also be the 'Achilles heel' of a solar-based sustainable energy system, tipping the choice to a nuclear breeder system.

Cook, G.M.; Spindler, W.C. & Grefe G.: "Overview of battery power regulation and storage", IEEE Transaction on Energy Conversion, vol. 6, no. 1, pp. 204-211, March 1991.

Battery energy systems are an electric utility technology whose applications are not yet fully demonstrated. The applications and benefits achieved by existing and planned facilities, and those that are possible, are discussed. The performance of existing facilities and the benefits predicted by models show that battery energy systems can be an economically attractive addition to the equipment now used to generate and transmit electric power.

Cook, G.M.; Spindler, W.C. & Grefe G.: "Overview of Battery Power Regulation and Storage", IEEE Power Engineering Review, vol. 11, no. 3, pp. 48, 1991.

Cox, D.R. & Krahn, R.L.: "Friction and windage loss tests of McNary generators with coupled and uncoupled turbine", AIEE Transactions, vol. 77, pp. 818-820, 1958.

Crary, S.B.; Herliz, I. & Favez, B.: "Report on the activities of Study Committee No. 13: Power System planning and operation", Report 331, 18th CIGRE Session, Paris, 1960.

Crompton, T.R.: "Battery Reference Book", Butterworth, London, 1990.

Crouch, D.R. & Reitz, J.W.: "Relating recombination mat separator properties to sealed lead/acid battery performance", Journal of Power Sources, vol. 31, no. 1-4, pp. 125-133, 1990.

Cruden A. & Dudgeon G.J.W.: "The impact of energy storage devices used in conjunction with renewable embedded generators, on the protection and control system", Seventh International Conference on Developments in Power System Protection, pp. 230-233, 2001.

This paper has described the drivers and background to the development of renewable energy in the UK. Within this context the authors identified the New Electricity Trading Arrangements (NETA) as a potential risk to the continuing development of renewable generation and proposed the use of an energy storage system (ESS) as a mechanism to alleviate these concerns. An initial study has concluded that the use of a hybrid ESS/wind farm under the NETA conditions would result in an increase in operating revenue. However preliminary protection investigations have highlighted concerns over appropriate control and protection under the particular scenarios of a change in operating mode from load (i.e. as an electrolyser) to a generator (i.e. to a fuel cell) and vice versa. Work is continuing to produce more detailed modelling results of such a system. It is believed this work will have relevance to the wider spread study of the application of ESS devices in general, for example for use as large scale devices to ensure network security in a power system with high penetrations of local, small-scale embedded generation.

Currence, E.J.; Plizga, J.E. & Nelson, H.N.: "Harmonic resonance at a medium-sized industrial plant", IEEE Transactions on Industry Applications, vol. 31, pp. 682-690, 1995.

Davidson, B.J. et.al.: "Large-scale Electric Energy Storage", IEE Proceedings, vol. 127, pt. A, pp. 345-385, July 1980.

Dell, R.M. & Rand, D.A.J.: "Energy storage - a key technology for global energy sustainability", Journal of Power Sources, vol. 100, no. 1-2, pp. 2-172001.

The quality of life today is dependent upon access to a bountiful supply of cheap energy. For a sustainable future, the energy should be derived from non-fossil sources; ideally, it should also be reliable and safe, flexible in use, affordable, and limitless. This paper examines the present global use of energy in its various forms, and considers projections for the year 2020 with particular attention to the harnessing of 'clean' and renewable forms of energy for electricity generation and road transportation. The incorporation of renewables is constrained in many instances by the variable and intermittent nature of their output. This calls for the practical application of energy-storage systems. An evaluation is made of the prospects of the candidate storage technologies - pumped-hydro, flywheels, hydrogen (for use in fuel cells), batteries - for application in centralized and distributed electricity supplies, and in electric and hybrid electric vehicles. The discussion concludes with the developments foreseen over the next 20 years.

Denholm, P. & Kulcinski, G.L.: "Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems", Energy Conversion and Management, vol. 45, no. 13-14, pp. 2153-2172, 2004.

Using life cycle assessment, metrics for calculation of the input energy requirements and greenhouse gas emissions from utility scale energy storage systems have been developed and applied to three storage technologies: pumped hydro storage (PHS), compressed air energy storage (CAES) and advanced battery energy storage (BES) using vanadium and sodium polysulphide electrolytes. In general, the use of energy storage with electricity generation increases the input energy required to produce electricity, as well as the total greenhouse gas emissions. Despite this increase, the life cycle GHG emission rate from storage systems when coupled with nuclear or renewable sources is substantially lower than from fossil fuel derived electricity sources. GHG emissions from PHS when coupled with nuclear and renewable energy systems are lower than those from BES or CAES. When coupled with fossil generation, CAES has significantly lower net GHG emissions than PHS or BES.

Demarest, M.; Taylor, P.; Achenbach, D. & Akhil, A.A.: "Battery storage all but eliminates diesel generator", Electrical World, vol. 211, no. 6, pp. 39, 1997.

Battery storage of electricity has some surprising benefits for island utilities - and it is not just peak shaving. A recently installed battery energy-storage system on the remote island of Metlakatla, Alaska, provides rapid spinning reserve, frequency control, and better power quality. When Metlakatla Power & Light's biggest customer added a chipper in 1986, MP&L's hydro-powered system struggled to address load swings estimated at about 500 kW. The subsequent addition of a 3.3-MW diesel for $2 million increased generating capacity to 8 MW but the new diesel still could not respond to the 900 kW maximum load swings MP&L was getting. A techno/economic feasibility study by GE Power Systems Division and GNB Industrial Battery confirmed that a 1-MW/1.4-MWh battery energy storage system (BESS) could proved the spinning reserve, frequency control and power-quality improvement that Metlakatla needed. The BESS project took 6 years from start to finish.

Deng, H.; Oruganti, R. & Srinivasan, D.: "PWM methods to handle time delay in digital control of an UPS inverter", IEEE Power Electronics Letters, vol. 3, no. 1, pp. 1-6, 2005.

With the popularity of micro-processors, digital controllers are widely used in uninterruptible power supply (UPS) inverters. These digital control systems of UPS inverters require a time interval for sampling and computation, which sometimes affects the performance of inverters. In this paper, the problem of time delay in digital control of a UPS inverter is discussed. Then two novel pulsewidth modulation (PWM) methods, the two-polarity PWM method and the asymmetric PWM method, are proposed to handle the time-delay problem. Both of these PWM methods can achieve a wide range of duty ratio between 0.05-0.95, which is independent of inverter model. Furthermore, they are easy to implement using a digital micro-controller. Experimental results are presented in the paper to verify feasibility of the proposed PWM methods.

Denholm, P.: "Improving the technical, environmental and social performance of wind energy systems using biomass-based energy storage", Renewable Energy, vol. 31, no. 9, pp. 1355-1370, 2006.

A completely renewable baseload electricity generation system is proposed by combining wind energy, compressed air energy storage, and biomass gasification. This system can eliminate problems associated with wind intermittency and provide a source of electrical energy functionally equivalent to a large fossil or nuclear power plant. Compressed air energy storage (CAES) can be economically deployed in the Midwestern US, an area with significant low-cost wind resources. CAES systems require a combustible fuel, typically natural gas, which results in fuel price risk and greenhouse gas emissions. Replacing natural gas with synfuel derived from biomass gasification eliminates the use of fossil fuels, virtually eliminating net CO2 emissions from the system. In addition, by deriving energy completely from farm sources, this type of system may reduce some opposition to long distance transmission lines in rural areas, which may be an obstacle to large-scale wind deployment.

DeVries, T.; McDowall, J.; Umbricht, N. & Linhofer, G.: "Cold storage - Battery energy storage system for Golden Valley Electric Association", ABB Review, no. 1, pp. 39-43, 2004.

DeWinkel, C. & Lamoree, J.D: "Storing power for critical loads", IEEE Spectrum, vol. 30, no. 6, pp. 38-43, 1993.

Superconducting magnetic-energy storage (SMES) units, originally proposed for use by utilities to help them meet peak electricity demands, are now commercially available. The first commercial SMES is a smaller unit (micro-SMES) for power quality uses. Micro-SMES stores and delivers much less electricity over much briefer periods - megawatts for seconds only. In an SMES system, the magnetic field produced by current flowing in a superconducting coil stores the energy. A cryogenic fluid keeps the coil at the temperature required for its material to become superconducting. Potential users, with an eye on uninterruptible power supplies, for instance, should weigh micro-SMES technology against battery, capacitor, flywheel, and other energy storage systems in terms of such characteristics as energy density, charge-discharge-cycle efficiency, environmental effects, and reliability. Those who stand to benefit most from micro-SMES technology may be the manufacturers with sensitive industrial processes, where the replacement of electromechanical control by digital equipment has entailed vulnerability to momentary lapses in power quality.

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Dyer, R.T.; McCue, D.R.; Williams, S.L.; Swencki, S.J. & Thoits, P.O.: "A static var system for starting and operating large synchronous compressor motors", IEEE Transactions on Industry Applications, vol. 23, pp. 166-172, 1987.

Eckroad, S.W. & Radimer, B.M.: "Review of engineering design considerations for battery energy management systems", IEEE Transaction on Energy Conversion, vol. 6, no. 2, pp. 303-309, June 1991.

> A review of existing literature, demonstration project experience, and current engineering understanding related to battery energy storage plant design issues is given. The focus is on how plant design is related to the application requirements and the unique characteristics of available equipment. A description of the major components of a battery energy storage plant is given. The utility applications for battery storage currently of interest are surveyed. Some of the many design issues are discussed, and some examples of potential design/cost tradeoffs are presented.

Ekdunge, P.: "A simplified model of the lead/acid battery", Journal of Power Sources, vol. 46, pp. 251-262, 1993.

Els, H.: "The Hydraulic Design of the Outlet Work for (Pump-) Turbines in a Shaft", Water Power and Dam Construction, 10/1987.

Ertl, H.; Kolar, J.W. & Zach, F.C.: "A novel multicell DC-AC converter for applications in renewable energy systems", IEEE Transactions on Industrial Electronics, vol. 49, no. 5, pp. 1048-1057, 2002.

> This paper presents a novel DC-AC converter for applications in the area of distributed energy generation systems, e.g., solar power systems, fuel-cell power systems in combination with supercapacitor or battery energy storage. The proposed converter is realized using an isolated multicell topology where the total AC output of the system is formed by series connection of several full-bridge converter stages. The DC links of the full bridges are supplied by individual DC-DC isolation stages which are arranged in parallel concerning the dc input of the. total system. Therefore, all switching cells of the proposed converter can be equipped with modern low-voltage high-current power MOSFETs, which results in an improved efficiency as compared to conventional isolated DC-AC converters. Furthermore, the cells are operated in an interleaved pulsewidth-modulation mode which, in connection with the low voltage level of each cell, significantly reduces the filtering effort on the AC output of the overall system. The paper describes the operating principle, analyzes the fundamental relationships which are relevant for component selection, and presents a specific circuit design. Finally, measurements taken from a 2-kW laboratory model are presented.

Fairley, P.: "Steady as she blows [wind power, energy storage]", IEEE Spectrum, vol. 40, no. 8, pp. 35-39, 2003.

> Power electronics and exotic energy storage devices are making wind power steady enough to compete with conventional electricity sources. Systems based on advanced power electronics and energy storage devices are massaging and managing power flows from wind turbines, enabling them to contribute to electricity grids without putting those grids at risk. Not only are the technologies making wind power more palatable to grid operators, they are even making it possible for engineers to finally harness wind energy's tremendous potential in wind-swept, remote locales. This article discusses the power electronic and energy storage technologies used in wind power.

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Ferencsik, J.J. & VanBuskirk, W.H.: "Electrical Design Aspects of Muddy Run Pumped Storage Plant", IEEE Transactions on Power Apparatus and Systems, vol. PAS-88, no. 8, pp. 1302-1309, August 1969.

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Fink, D.G. & Carroll, J.M.: "Frequency Converter with D-C Link", Section 12-31 in Standard Handbook for Electrical Engineers, Tenth Edition, McGraw-Hill, New York, 1968.

Fischer, M.H.; Fonseca, G.W. & Gilbert, S.M.: "Design Features of Mt. Elbert Pumped-Storage Powerplant", Paper F75 443-2, presented at the IEEE/PES Summer Meeting, 1975.$

Fitzgerald, J.P.: "Synchronous starting of Senecirka pumped storage plant", IEEE Transactions on Power Apparatus and Systems, vol. PAS-88, pp. 307-315, 1969.

Florjančič, D.: "The pump-turbine as a further development of the storage pump", Sulzer Tech. Rev., vol. 47, pp. 139-142, 1965.

Forster, M.: "Theoretical investigation of the system SnOx/Sn for the thermo-chemical storage of solar energy", Energy, vol. 29, no. 5-6, pp. 789-799, 2004.

> The thermodynamic data of the system SnO2/SnO/Sn in the absence and presence of CH4 and C are calculated as a function of temperature. The direct dissociation of SnOx without any reducing substances needs temperatures T>2000 K at 1 bar. In the presence of CH4 or C, SnOx can be reduced at T<1250 K. The production of H2 from Sn, SnO and H2O is investigated. A real overall solar yield @hreal is defined which compares the output of real fuel cells, fed by solar-produced chemicals, with the total solar input necessary to produce these chemicals. @hreal is then used to find the most promising thermochemical reaction of the system SnO2/SnO/Sn+C/CH4. The optimal reaction is SnO2+2CH4@?Sn+2CO+4H2, proceeding at 980 K (@DrG=-60 kJ), which is followed by Sn+2H2O@?SnO2+2H2. CO and H2 are then fed to fuel cells producing electricity with @hreal=0.23. The amount of solar upgrading of the fossil fuels CH4 and C is given. A combination of solar reactor, heat recovery device and a following reactor to produce H2 is proposed. The dimension, volume and mass flow of the solar reactor are calculated and the amount of simultaneously produced electricity is given.

Fostiak, R.J. & Davis, H.R.: "Electrical Features of the Rocky Mountain Pumped-Storage Project", IEEE Transactions on Energy Conversion, vol. 9, no. 1, pp. 206-213, March 1994.

Fukasu, S.; Tazuke, O & Hiroyoshi, H.: "Recent Trends in Hydroelectric Power Station Equipment", Hitachi Review, Special issue, No. 13.

Furusawa, Ken; Sugihara, Hideharu; Tsuji, Kiichiro & Mitani, Yasunori: "A study of economic evaluation of demand-side energy storage system in consideration of market clearing price", Electrical Engineering in Japan, vol. 158, no. 1, pp. 22-35, 2007.

> In Japan the electricity market will open on April 1, 2004. Electric utility, Power Producer and Supplier (PPS), and Load Service Entity (LSE) will join the electricity market. LSEs purchase electricity based on the Market Clearing Price (:MCP) from the electricity market. LSEs supply electricity to the customers that contracted with the LSEs on a certain electricity price, and one to the customers that introduced Energy Storage System (:ES) on a time-of-use pricing. It is difficult for LSEs to estimate whether they have any incentive to promote customers to introduce ES or not. This paper evaluates the reduction of LSEs' purchasing cost from the electricity market and other LSEs' purchasing cost by introducing ES to customers. It is clarified which kind of customers has the effect of decreasing LSEs' purchasing cost and how much MCP of the whole power system the demand-side energy storage systems change. Through numerical examples, this paper evaluates the possibility of giving the cost merit to both customers with energy storage systems and LSE by using real data for a year's worth of MCP.

Furuya, S.; Fujiki, S.; Hioki, T.; Yanagisawa, T.; Okazaki, S. & Kobayashi, S.: "Development and Achieved Commercial Operation Experience of the World's First Commissioned Converter-fed Variable-speed Generator-motor for a Pumped Storage Power Plant", Report 11-104, CIGRE Session, Paris, 30th August 5th September 1992.

Galanos, G.D.; Hatziadoniu, C.I.; Cheng, X.-J. & Maratukulam, D.J.: "Advanced static compensator for flexible AC transmission", IEEE Transactions on Power Systems, vol. 8, no. 1, pp. 113-121, 1993.

An advanced static VAr compensator capable of operating in all four quadrants of the P-Q plane is presented. It is realized by combining a GTO-controlled inverter with a battery energy storage system and a GTO-switched damping resistor. A hierarchically structured control system that fully utilizes the capabilities of the compensator to provide reactive power support in steady-state operation and both real and reactive power modulation in the event of power oscillations is developed. Results from simulation studies are presented to demonstrate the effectiveness of this compensator in improving the loadability of long transmission lines and in providing damping in interarea oscillations.

Gamlesaeter, K.: "Starting methods for pump storage units", Electra, no.134, pp. 14-21, February 1991.

The choice of method for starting large units in pumping mode is an important part of the planning of pumped storage power plants. It is partly limited by restrictions of grid voltage drop, starting time and equipment cost but priorities based on knowledge and experience play an important part in the choice procedure. Here, the author makes available to users and manufacturers the practice and experience of starting methods for pumped storage power plants over the last 20 years. It is expected that the knowledge of the criteria of choice and preference of starting methods will come in useful in the planning of future pumped storage power plants.

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Gersdorf, B.V.: "Das Pumpspeicherwer Rönkhausen", Elektrizitätswirtschaft, vol. 67, November 20, 1967.

Gertmar, L. & Sandarangani, C.: "On modelling, design and measurements of the inverter fed high speed induction motor", ABB Corporate Research, Västerås, 19??.

Ghedamsi, K.; Aouzellag, D. & Berkouk, E.M.: "Performance Analysis of a Flywheel Energy Storage System", Journal of Electrical Systems, vol. 4, no. 2, pp. 248-258, 2008.

The flywheel energy storage systems (FESSs) are suitable for improving the quality of the electric power delivered by the wind generators and to help these generators to contribute to the ancillary services. In this paper, a flywheel energy storage system associated to a grid connected variable speed wind generation (VSWG) scheme using a doubly fed induction generator (DFIG) is investigated. Therefore, the dynamic behavior of a wind generator, including models of the wind turbine (aerodynamic), DFIG, matrix converter, converter control (algorithm of VENTURINI) and power control is studied. This paper investigates also, the control method of the FESS with a classical squirrel-cage induction machine associated to a VSWG using back-to-back AC/AC converter. Simulation results of the dynamic models of the wind generator are presented, for different operating points, to show the good performance of the proposed system.

Gilon, D.: "Design and Tests of a 6 MW, 10 000 rpm Induction Motor", Fifth International Conference on Electrical Machines and Drives, London, 11-13 September 1991, Conference Publication Number 341, The Institution of Electrical Engineers, London, 1991.

Gish, W.; Schurz, J.; Milano, B. & Schleif, F.: "An Adjustable Speed Synchronous Machine for Hydroelectric Power Applications", IEEE Transactions on Power Apparatus and Systems, vol. PAS-100, no. 5, pp. 2171-2176, May 1981.

Gove, R.M.; Murray, A.T.L.; Cheseldine,I.H.B.; Alyward, J.H. & Buttrey, M.: "Electrical design considerations for reversible pumped storage hydroelectric projects", Report 11-02, 22nd CIGRE Session, Paris, 1968.

Greenblatt, J.B.; Succar, S.; Denkenberger, D.C.; Williams, R.H. & Socolow, R.H.: "Baseload wind energy: modeling the competition between gas turbines and compressed air energy storage for supplemental generation", Energy Policy, vol. 35, no. 3, pp. 1474-1492, 2007.

The economic viability of producing baseload wind energy was explored using a cost-optimization model to simulate two competing systems: wind energy supplemented by simple- and combined cycle natural gas turbines (''wind+gas''), and wind energy supplemented by compressed air energy storage (''wind+CAES''). Pure combined cycle natural gas turbines (''gas'') were used as a proxy for conventional baseload generation. Long-distance electric transmission was integral to the analysis. Given the future uncertainty in both natural gas price and greenhouse gas (GHG) emissions price, we introduced an effective fuel price, pNGeff, being the sum of the real natural gas price and the GHG price. Under the assumption of pNGeff=$5/GJ (lower heating value), 650W/m2 wind resource, 750km transmission line, and a fixed 90% capacity factor, wind+CAES was the most expensive system at @?6.0/kWh, and did not break even with the next most expensive wind+gas system until pNGeff=$9.0/GJ. However, under real market conditions, the system with the least dispatch cost (short-run marginal cost) is dispatched first, attaining the highest capacity factor and diminishing the capacity factors of competitors, raising their total cost. We estimate that the wind+CAES system, with a greenhouse gas (GHG) emission rate that is one-fourth of that for natural gas combined cycle plants and about one-tenth of that for pulverized coal plants, has the lowest dispatch cost of the alternatives considered (lower even than for coal power plants) above a GHG emissions price of $35/tCequiv., with good prospects for realizing a higher capacity factor and a lower total cost of energy than all the competing technologies over a wide range of effective fuel costs. This ability to compete in economic dispatch greatly boosts the market penetration potential of wind energy and suggests a substantial growth opportunity for natural gas in providing baseload power via wind+CAES, even at high natural gas prices.

Grein, H. Jaquet, M.: "Einige hydraulische Aspekte beim Anfahren von Speicherpumpen und Pumpturbinen großer Leistung", Escher Wyss Mitteilungen, 1975/1.

Grein, H. & Baumann, K.M.J.: "Die Ereignisss der Inbetriebsetzung der Pumpturbine Vianden 10" Escher Wyss Mitteilungen, 1976/2.

Gutierrez-Vera, J.: "Use of renewable sources of energy in Mexico case: San Antonio Agua Bendita", IEEE Transaction on Energy Conversion, vol. 9, no. 3, pp. 442-450, 1994.

This paper presents a project undertaken in Mexico to electrify the remote village of San Antonio Agua Bendita (SAAB) using a custom designed hybrid power system. The hybrid power system will provide grid quality electricity to this community which would otherwise not have been electrified via traditional distribution lines. The hybrid power system was designed to electrify the entire community, incorporate multiple sources of renewable power with on-demand power, operate autonomously, and be cost effective in dollars per watt of electricity generated over the system's usable life. A major factor in the success of this project is the use of renewable energy for economic development and community partnership. Many rural electrification projects have provided power for domestic use but few have successfully provided power to improve the economic condition of the people served by the system. The SAAB hybrid avoids this pitfall by providing 120 VAC power at 60 Hz to anticipated industrial loads in the village, as well as providing grid quality power for domestic use. The system consists of the following modules: a controller, battery storage, a PV array, two 10 kW wind turbines, a diesel generator, a micro-hydro generator, power output control.

Gyuk, I.; Kulkarni, P.; Sayer, J.H.; Boyes, J.D.; Corey, G.P. & Peek, G.H.: "The United States of storage", IEEE Power and Energy Magazine, vol. 3, no. 2, pp. 31-39, 2005.

The collaboration between the states and the DOE's Energy Storage Research Program is proving to be an outstanding success. The selected projects show a good portfolio of advanced energy storage media: a ZnBr flow battery, the NaS battery, supercapacitors, and flywheels. The applications are equally varied: mitigation of substation congestion, grid frequency control, load management, and stabilization of a microgrid. The goal of these partnerships with the states is to demonstrate electric energy storage as a technically viable, cost-effective, and broadly applicable option for increasing the reliability of the electricity system and for electric energy management.

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Hamlin, F.C.: "Electrical Features of Smith Mountain Hydro Project, Appalachian Power Company", IEEE Transactions on Power Apparatus and Systems, vol. PAS-88, no. 4, pp. 299-306, April 1969.

Hammons, T.J.; Loughran, J.; Cochran, A.M. & Gove, R.M.: "Starting reversible pump turbines", Paper C 14, Proceedings of the 3rd international power systems computational conference, Rome, 1969.

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Hangeland, J.: "Operating experience with large reversible pump turbines – reliability and availability", Paper 45, presented to the International congress on modern electric power stations, AIM, Liege, 1970.

Happoldt, H.K. et al.: "Present State of Pumped Storage in Europe", IEEE Transactions on Power Apparatus and Systems", vol. PAS-82, no. 10, pp. 618-631, October 1963.

Harper, A.D.: "Thermochemical power systems for underwater applications", Proceedings of the Sixth International Symposium on Unmanned Untethered Submersible Technology, pp. 136-152, 1989.

> Current trends toward larger unmanned vehicles with more ambitious missions dictate significant improvements in power system installed energy density compared to either lead-acid or silver-zinc battery/motor systems. Analytical comparisons of various potential power system mechanizations indicate that thermochemical power systems offer the potential for the needed increases in energy density on both weight and volume bases. These systems represent a rapidly maturing technology; therefore, directed development of key thermochemical power system parameters is strongly recommended to achieve UUV (unmanned underwater vehicle) speed and range goals. For example, it is shown that a neutrally buoyant system derived from the MK 50 Torpedo stored chemical energy propulsion system (SCEPS) can produce 200 to 300 Watt-hr/Ib depending on mission characteristics. The characteristics of other potential approaches, such as advanced batteries and fuel cells, are included in these system comparisons. A variety of thermochemical heat sources are considered including SCEPS, advanced versions of SCEPS, and high-temperature diesel fuel-oxygen combustion systems. Compact heat engine designs for both Rankine steam turbine and Brayton gas turbine engines are included in these study results. In addition, a discussion of approaches capable of achieving the required endurance with SCEPS-type systems is presented.

Hartmann, E., Helmer, F. & Latrille, W.: "Neue 105-MW-Pumpturbinenanlage im Koepchenwerk", Elektrizitätswirtschaft, vol. 86, no. 24, pp. 1037-1043, 23 November 1987.

Harty, F.R. Jr; Depenbrock, F.; Ward P.W. & Shectman, D.L.: "Options in energy storage technologies", The Electricity Journal, vol. 7, no. 6, pp. 21-26, 1994.

> For an electric power transmission system, the use of energy storage technology provides 2 major benefits - the more efficient use of existing systemwide plant investment, and flexibility in systemwide operations and better response to price changes. The most commonly used energy storage technology is hydro pumped storage, which has evolved into advanced pump storage (APS), which provides greatly enhanced operational flexibility. Other technologies that are being pioneered as options for energy storage are compressed air storage, battery energy storage systems (BESS), and superconducting magnetic energy storage (SMES). Dynamic benefits of these technologies vary with their ability to respond to changes in load and to sustain their assistance in controlling voltage, frequency, and system stability. The interaction times range from milliseconds (for BESS and SMES) to seconds (for APS) to minutes. The ultrafast ramping rates of BESS, SMES, and APS have the potential to provide valuable services such as: system stability, peak shaving, load following, spinning reserve, power factor correction, and frequency regulation.

Heitner, K.L.: "Energy storage systems for improved load management", Power Engineering, vol. , pp. 56-59, September, 1979.

Henriksen, H.M. & Bruecl, H.: "Variable frequency starting equipment for pumped storage projects", IEEE Transactions on Power Apparatus and Systems, vol. PAS-101, no. 9, pp. 3206-3210, September 1982.

Henry, L.F.; Miller, D.L. & Whippen, W.G.: "Mechanical and Hydraulic Considerations When Starting Reversible Pump/Turbines", Paper presented at the International Symposium on Modern Electric Plants, Liege, October 1974.

Hickok, H.N.: "Adjustable speed – A tool for saving energy losses in pumps, fans, blowers, and compressors", IEEE Transactions on Industry Applications, vol. 21, pp. 124-136, 1985.

Hirabayashi, H.; Makida, Y.; Nomura, S. & Shintomi, T.: "Liquid Hydrogen Cooled Superconducting Magnet and Energy Storage", IEEE Transactions on Applied Superconductivity, vol. 18, no. 2, pp. 766-769, 2008.

> The earth faces environmental problems such as temperature increase and energy crisis. One of the solutions for the problems may be to put hydrogen energy to practical use. Superconducting devices for power applications are promising technologies for saving energy. By convergence of high temperature superconductors (HTS) or MgB2 and liquid hydrogen, advanced energy systems can be introduced to power applications. We have proposed an emergency power supply system in combination with an HTS or MgB2 magnet (SMES) cooled with liquid hydrogen and fuel cells for hospitals, intelligent buildings, advanced factories like semiconductor industry, and so on. The superconducting magnet has merits of fast time response and high input/output electric power. On the other hand, the liquid hydrogen can store energy with high density and the fuel cell can supply electricity with high efficiency. The combination of these devices produces synergistic effects for environmentally friendly and energy saving measures. The development schedule and design for the prototype of the emergency power supply system are described.

Hirachi, K.; Yamanaka, M.; Takada, T.; Mii, T. & Nakaoka, M.: "Feasible developments of utility-interactive multi-functional bidirectional converter for solar photovoltaic generating system incorporating storage batteries", 26th Annual IEEE Power Electronics Specialists Conference, PESC '95, vol. 1, pp. 536-541, 1995.

> In recent years, expecting photovoltaic generating system using utility-interactive PWM inverters have attracted special interest as effective means to broaden the application areas of clean natural energy sources without using a large amount of fossil fuels. This paper presents a unique circuit and system configurations for the solar battery and storage battery in such a PV power system. The system implementation incorporating the control strategy introduced in switching schemes between stand-alone and utility-interactive operations is discussed. Furthermore the experimental results tested through trially-produced 3 kVA prototype power converters and their effectiveness are illustrated and evaluated.

Hiraki, E.; Kurokawa, M.; Sugimoto, S. & Nakaoka, M.: "A novel resonant DC link bidirectional three phase PWM converter for battery energy storage system", Proceedings of the IEEE International Conference on Power Electronics and Drive Systems, vol. 1, pp. 163-168, 1997.

> In this paper, a simple prototype of a quasi-resonant DC link (QRDCL) voltage-fed bidirectional power converter operating in the zero voltage soft-switching PWM mode is presented for a battery energy storage system (BESS). The operating principle of this QRDCL circuit and multi-functional control-based power converter system, including PWM inverter mode in which energy flows through from the battery bank to the three phase utility-grid and an active PWM power converter mode in which energy flows through from the utility-grid to the battery bank are described. The multi-functional operating characteristics of this three-phase soft-switching ZVS-PWM bidirectional power converter with a QRDCL for BESS is demonstrated under the conditions of peak-cut mode and battery charging mode in comparison with a three-phase hard-switching PWM bidirectional power converter. Its effectiveness is proved by simulation analysis.

Hirose, S.; Seki, N.; Higa, O.; Miguchi, Y.; Takahashi, K.; Shibata, T.: "Multi-microcomputer-based controller for 12 MW GTO power conditioning systems", Power Electronics Specialists Conference, vol. 2, pp. 611-618, 1988.

A multimicrocomputer controller was fabricated for a 12 MW power conditioning system (PCS). The configuration of the PCS, which consists of a 12 MW GTO (gate-turn-off) inverter, series reactors, output transformers, AC circuit breakers, and a PCS controller, is described. The functions of the controller are outlined. Results of performance tests that were conducted on a 20 kW PCS model and on the 12 MW PCS are reported, reflecting the excellent performance of the controller.

Hoffeins, H. & Mohmeyer, K.-U.: "Betriebserfahrungen mit dem Luftspeicher-Gasturbinen-Kraftwerk Huntorf", Brown Boveri Technik, vol. 86, no. 6, pp. 297-305, June 1986.

Hsu, M.: "Light-weight electrochemical converter for space power applications", Proceedings of the SPIE - The International Society for Optical Engineering, vol. 871, pp. 96-102, 1988.

An innovative concept for space power systems utilizes an electrochemical-loop, which comprises a high temperature electrolytic cell and a low temperature fuel cell. In the electrolytic cell, the working fluid is electrolyzed using combined thermal and electrical input. The products of the electrolysis are recombined in a lower temperature fuel cell, generating more voltage output than required to operate the electrolytic cell. The excess electricity from the loop is available for external loads. The thermal energy can be made available from a nuclear reactor. The zirconia cells of solid oxide electrolyte under development by Ztek would serve as the high temperature electrolytic cell. The low temperature fuel cells, which are under development in various space programs, can be adapted for this system. Studies suggest that this system is a desirable light-weight option in meeting future space power needs. Recent technical advances in zirconia cell development have brought the hardware loop integration close to realization.

Huang, K.-L.; Li, X.-g.; Liu, S.-q.; Tan, N.; Chen, L.-q.: "Research progress of vanadium redox flow battery for energy storage in China", Renewable Energy, vol. 33, no. 2, pp. 186-192, 2008.

Principle and characteristics of vanadium redox flow battery (VRB), a novel energy storage system, was introduced. A research and development united laboratory of VRB was founded in Central South University in 2002 with the financial support of Panzhihua Steel Corporation. The laboratory focused their research mainly on the selection and preparation of electrode materials, membrane material and modification, stable concentrated electrolyte producing approach, test cell configuration design and optimization. Some relevant foundation problems, such as state of vanadium in sulfurous acid with various additives, the difference of electrochemical reaction rate in anode and in cathode, the crossover of vanadium ions and so on, have been emphasized. The details of these studies have been given and discussed. A 5kW VRB stack was fabricated in the laboratory and its performances, especially electrochemical performance such as voltage efficiencies, energy efficiencies, and durability, were fully tested. The results will be shown in the talk. The key technologies of developing VRB, such as to improve the activity of its electrode materials, the stability of electrolyte and selectivity of separator, were also discussed. In addition, the research progresses in other laboratories in China were briefly introduced.

Humphreys, K.K. & Brown, D.R.: "Life-cycle cost comparisons of advanced storage batteries and fuel cells for utility, stand-alone, and electric vehicle applications", Report PNL-7203, January, 1990.

This report presents a comparison of battery and fuel cell economics for ten different technologies. To develop an equitable economic comparison, the technologies were evaluated on a life-cycle cost (LCC) basis. The LCC comparison involved normalizing source estimates to a standard set of assumptions and preparing a lifetime cost scenario for each technology, including the initial capital cost, replacement costs, operating and maintenance (O&M) costs, auxiliary energy costs, costs due to system inefficiencies, the cost of energy stored, and salvage costs or credits. By considering all the costs associated with each technology over its respective lifetime, the technology that is most economical to operate over any given period of time can be determined. An analysis of this type indicates whether paying a high initial capital cost for a technology with low O&M costs is more or less economical on a lifetime basis than purchasing a technology with a low initial capital cost and high O&M costs. It is important to realize that while minimiz-

ing cost is important, the customer will not always purchase the least expensive technology. The customer may identify benefits associated with a more expensive option that make it the more attractive over all (e.g., reduced construction lead times, modularity, environmental benefits, spinning reserve, etc.). The LCC estimates presented in this report represent three end-use applications: utility load-leveling, stand-alone power systems, and electric vehicles.

Hunt, G.W.: "Design and commissioning of a valve-regulated lead/acid battery energy-storage system for backing up critical environmental loads", Journal of Power Sources, vol. 67, no. 1-2, pp. 179-186, 1997.

Momentary and sustained electrical power interruptions and voltage depressions represent two of the most difficult and important power quality and delivery problems that face many industrial and commercial users. There is a definite need at many industrial processing plants and commercial users of electrical power to have a dependable, efficient and controllable source of real and reactive power that is available instantly to support large electrical loads (greater than 5 MVA), even if the incoming utility a.c. connection is lost. When power is interrupted or lost, the results can be extremely disruptive for critical processes and cause lost production, costly downtime and loss of customer good will, and in certain industries, can lead to environmental damage through the release of toxic emissions into the air. Recently, this challenge was faced by GNB Technologies at its lead reclaiming and smelting facility in Vernon, CA, USA. This study describes a versatile, cost-effective, workable solution to the problem that has resulted in the design and installation of a 5 MVA, 3.5 MWh battery energy storage system (BESS) which provides uninterruptible power to the critical environmental control equipment throughout the plant. The BESS at Vernon provides the required power, combined with both voltage and frequency control, to allow the plant to tolerate disconnection from the utility grid without suffering unacceptable impacts on critical loads. The system also provides the company with a demand-side energy management system for conducting daily peak shaving of energy demand and, thereby, reduces its electrical bills.

Hunt, G.W.: "Valve regulated lead/acid battery systems", Power Engineering Journal, vol. 13, no. 3, pp. 113-116, 1999.

The Power Control Division of GNB Technologies commissioned on the 13th May 1996 a new facility housing a 5 MW battery energy storage system (BESS) at GNB's Lead Recycling Center in Vernon, California, USA. The Vernon BESS is the largest known installation of its kind in the world owned and operated by an industrial manufacturer to support critical manufacturing process equipment, including the operation of emission control systems associated with handling lead dust. GNB's primary concern is to assure the continual operation of these systems during a power outage.

Hunt, G.W.: "Operational experience and performance characteristics of a valve-regulated lead-acid battery energy-storage system for providing the customer with critical load protection and energy-management benefits at a lead-recycling plant", Journal of Power Sources, vol. 78, no. 1-2, pp. 171-175, 1999.

The Power Control Division of GNB Technologies, commissioned on May 13, 1996 a new facility which houses a 5-MW battery energy-storage system (BESS) at GNB's Lead Recycling Centre in Vernon, CA. When the plant loses utility power (which typically happens two or three times a year), the BESS will provide up to 5 MW of power at 4160 VAC in support of all the plant loads. Since the critical loads are not isolated, it is necessary to carry the entire plant load (maximum of 5 MVA) for a short period immediately following an incident until non-critical loads have been automatically shed. Plant loading typically peaks at 3.5 MVA with critical loads of about 2.1 MVA. The BESS also provides the manufacturing plant with customer-side-of-the-meter energy management options to reduce its energy demand during peak periods of the day. The BESS has provided a reduction in monthly electric bills through daily peak-shaving. By design, the battery can provide up to 2.5 MWh of energy and still retain 2.5 MWh of capacity in reserve to handle the possibility of a power outage in protecting the critical loads for up to 1 h. By storing energy from the utility during off-peak hours of the night in the batteries when the cost is low (US4.5&; per kWh), GNB can then discharge this energy during high demand periods of the day (US$14.50 per kW). For example, by reducing its peak demand by 300 kW, the lead-recycling centre can save over US$4000 per month in its electric bills. The BESS at Vernon represents a first large-scale use of valve-regulated lead-acid batteries in such a

demanding application. This paper presents a summary of the operational experience and performance characteristics of the BESS over the past 2 years.

Hurwitch; J.W. & Carpenter, C.A.: "Technology and application options for future battery power regulation", IEEE Transaction on Energy Conversion, vol. 6, no. 1, pp. 216-223, March 1991.

Future battery storage applications and technologies are discussed. Trends in the utility industry and the future role of battery storage are addressed, with an emphasis on power regulation options. Discussions on battery storage for specific power regulation applications are presented, as well as the status of advanced battery development in Europe, Japan, and the United States.

Högberg, K.-E.: "Frekvensomriktare för start av aggregaten i Foyers pumpkraftverk", ASEA Tidning, vol. 68, no. 1, pp. 3-8, 1976.

Högberg, K.-E.: "Frequency convertors for starting the motor/generators for Foyers pumped storage power station", ASEA Journal, vol. 49, no. 3, pp. 51-56, 1976.

Iijima, H.; Takanashi, T., Tsunoda, S., Harada, K., Fujisaki, M. & Ogita, T.: "Bajina Basta Pumped Storage Power Station - World's Highest Head, High-speed and Large Capacity", Toshiba Review, no. 100, pp. 47-53, November-December 1975.

Iijima, H.; Tsunoda, S., Terashima, T., Kawase, Y. & Ogita, T.: "World's Highest Head, Large Pumped Storage Equipment for Ohira Power Station", Toshiba Review, vol. , pp. 14-19, May-June, 1974.

Inoue,H., Sato, J., Ichinose, M. & Suzuki, N.: "Field Test Results on Diagonal-flow Type Reversible Pump-turbines and Generator-motors for Takane No. 1 Power Station", Hitachi Review, vol. 20, no. 7, pp. 268-275, July 1971.

Jaccard, D.: "Choice of electrical characteristics of pump-turbine installations observations during studies and operation", Report 11-09, 22nd CIGRE Session, Paris, 1968.

Jaquet, M.: "Einige spezielle Probleme bei der Entwicklung von Pumpturbinen", Escher Wyss Mitteilungen", 174/2.

Jin, J.X.: "HTS energy storage techniques for use in distributed generation systems", Physicirka C: Superconductivity, vol. 460-462, pp. 1449-1450, 2007.

Distributed generation is expected to play an important role in the future with growth in electric load, enhancing economical efficiency and protection of the environment. Energy storage technology is one of the effective methods to ensure the quality of the electrical power supply and the effective operation of the distributed generation systems. In this paper, several main energy storage technologies are compared with regard to their performances. Especially the use of high temperature superconducting (HTS) energy storages, i.e. in forms of superconducting magnetic energy storage and flywheel energy storage, will be analyzed with regard to the device performances in distributed generation systems.

Johansson, K.-E.: "Beräkning av den kritiska delen av startförloppet vid en "Back-to-Back"-start för Foyers pumpkraftverk", PM FKH, ASEA, Februari 1971.

Johnsson, G.D.: "Pumped storage: An evaluation of the progress and experience to date with large reversible units", Paper 156, Section C_2, VII World Power Conference, Moscow, 1968.

De Jong, H.C.J.: "Starting performance of synchronous motors with laminated salient poles", IEEE Transactions, vol. PAS-87, pp. 1083-1098, 1968.

Jung, K.-H.; Kim, H. & Rho, D.: "Determination of the installation site and optimal capacity of the battery energy storage system for load leveling", IEEE Transaction on Energy Conversion, vol. 11, no. 1, pp. 162-167, 1996.

This study aims to show methods of determining the installation site and the optimal capacity of a battery energy storage system (BESS) to attain load leveling. The methods are based on the hardware characteristics of 20 kW/100 kWh and 1 MW/4 MWh prototype BESSs, which are already developed and are being developed, respectively. The candidate site of BESS installation is the secondary side of a distribution substation's main transformer (MTR). These tasks are performed by first classifying the load pattern of an MTR and comparing it to the load pattern of a total power system. If the load factor improves, then the location is determined to be a BESS installation site. Subsequently, the optimal BESS capacity for an MTR is determined using the given operation pattern, the charging/discharging characteristics and efficiency. Computational experimentation was performed on an actual distribution system in Korea. After determining the optimal capacity, the authors verified that installing the BESS on the selected MTR improved both daily and nightly load factors.

Jäger, H. & Mühlöcker, H.: "Entwurf und Bemessung der Hauptmaschinensätze der Pumpspeicherwerks Waldeck II", Elektrizitätswirtschaft, vol. 70, pp. 685-691, 1971.

Kalaitzakis, K.C. & Vachtsevanos G.J.: "On the Control and Stability of Grid Connected Photovoltaic Sources", IEEE Transactions on Energy Conversion, vol. 2, no. 4, pp. 556-562, December 1987.

Kalaitzakis and Vachtsevanos proposed a methodology for the effective integration of photovoltaic devices into the electric utility distribution network operations. They focused on the storage requirements for control and stability purposes, power flow control, and power modulating device contributing to the improvement of system stability. System stability can be improved by monitoring the variations in system frequency, utility grid bus voltage, and the real power at the inverter output bus. Finally, their simulation studies indicate that an application of the proposed control approach may result in reduced load following requirements for conventional power generating units, and better power quality and stability of the interconnected system.

Kaldellis, J.K. & Zafirakis, D.: "Optimum energy storage techniques for the improvement of renewable energy sources-based electricity generation economic efficiency", Energy, vol. 32, no. 12, pp. 2295-2305, 2007.

The high wind and solar potential along with the extremely high electricity production cost met in the majority of Greek Aegean islands comprising autonomous electrical networks, imply the urgency for new renewable energy sources (RES) investments. To bypass the electrical grid stability constraints arising from an extensive RES utilization, the adaptation of an appropriate energy storage system (ESS) is essential. In the present analysis, the cost effect of introducing selected storage technologies in a large variety of autonomous electrical grids so as to ensure higher levels of RES penetration, in particular wind and solar, is examined in detail. A systematic parametrical analysis concerning the effect of the ESSs' main parameters on the economic behavior of the entire installation is also included. According to the results obtained, a properly sized RES-based electricity generation station in collaboration with the appropriate energy storage equipment is a promising solution for the energy demand problems of numerous autonomous electrical networks existing worldwide, at the same time suggesting a clean energy generation alternative and contributing to the diminution of the important environmental problems resulting from the operation of thermal power stations.

Kambe, A.; Kurokawa, M.; Chibani, A. & Nakaoka, M.: "A novel resonant DC link circuit with two level PWM control scheme and its application to three-phase voltage-fed converter operating at new pulse vector modulation", Proceedings of the IEEE Power Conversion Conference, vol. 1, pp. 325-330, 1997.

This paper presents a novel prototype of resonant DC link with a two-level PWM control scheme and a three-phase voltage-fed PWM inverter with a resonant DC link. This resonant DC link circuit is capable of controlling two-level PWM modes; a clamped supply voltage PWM and zero voltage PWM modes in the DC bus line can operate under the principle of zero voltage and zero current soft-switching. The operating analysis is carried out and a design procedure of this resonant DC link is described on the basis of simulation results. A three-phase voltage-fed inverter and power converter using this unique resonant DC link are analyzed which operate under a new pulse vector modulation scheme and their performances in a utility-interactive power processor for a battery energy storage system (BESS) are evaluated and discussed, including a reactive current compensator and active power filter using this resonant DC link.

Karden, E.; Mauracher, P. & Schope, F.: "Electrochemical modeling of lead acid batteries under operating conditions of electric vehicles", J. Power Sources, vol. 64, pp. 175–180, 1997.

Karden, E.; Ploumen, S.; Fricke, B.; Miller, T. & Snyder, K.: "Energy storage devices for future hybrid electric vehicles", Journal of Power Sources, vol. 168, no. 1, pp. 2-11, 2007.

Powertrain hybridization as well as electrical energy management are imposing new requirements on electrical storage systems in vehicles. This paper characterizes the associated vehicle attributes and, in particular, the various levels of hybrids. New requirements for the electrical storage system are derived, including: shallow-cycle life, high dynamic charge acceptance particularly for regenerative braking and robust service life in sustained partial-state-of-charge usage. Lead/acid, either with liquid or absorptive glass-fibre mat electrolyte, is expected to remain the predominant battery technology for 14V systems, including micro-hybrids, and with a cost-effective battery monitoring system for demanding applications. Advanced AGM batteries may be considered for mild or even medium hybrids once they have proven robustness under real-world conditions, particularly with respect to cycle life at partial-states-of-charge and dynamic charge acceptance. For the foreseeable future, NiMH and Li-ion are the dominating current and potential battery technologies for higher-functionality HEVs. Li-ion, currently at development and demonstration stages, offers attractive opportunities for improvements in performance and cost. Supercapacitors may be considered for pulse power applications. Aside from cell technologies, attention to the issue of system integration of the battery into the powertrain and vehicle is growing. Opportunities and challenges for potential ''battery pack'' system suppliers are discussed.

Kashem, M.A. & Ledwich, G.: "Energy requirement for distributed energy resources with battery energy storage for voltage support in three-phase distribution lines", Electric Power Systems Research, vol. 77, no. 1, pp. 10-23, 2007.

Integration of distributed energy resources (DER) into distribution systems is a new concept for improving system capacity and stability, feeder voltage, and supply quality and reliability. This paper has addressed voltage support in distribution systems by energy injection from a battery storage distributed energy system. An operation strategy for an inverter interface battery energy storage DER has been developed for maximum improvement in feeder voltage with minimum energy injection from the DER. A control strategy has been proposed for inverter based battery storage DER to regulate network voltage effectively, through operating the DER to generate real (P) and reactive (Q) power with Q priority. The implementation of the inverter interface DER with battery energy storage will save fuel cost of DER but be of much higher capital cost than using a rotary generator. The proposed technique has been evaluated by simulation on a three-phase distribution system with time varying loads. Test results indicate that DER operating with Q priority offers the best solution for maximum voltage improvement. The results also confirm that DER injecting P and Q at the ratio of maximum voltage sensitivity of line presents better solution for power loss reduction than the solution offered by the DER operating with Q priority.

Kaufmann, J.P.: "The Dimensioning of Pump-Turbines", Water Power & Dam Construction, vol. 29, no. 8, August 1977.

Kaufmann, J.P.: "The Dimensioning of Pump-Turbines", Water Power & Dam Construction, vol. 29, no. 9, September 1977.

Kawabata, T.; Doi, S.; Morikawa, T.; Nakamura, T. & Shigenobu, M.: "Large Capacity Parallel Redundant Transistor UPS," 1983 IPEC-Tokyo Conference Record, vol. 1, pp. 660-671, 1983.

Kawann, C. & Emanuel, A.E.: "Passive shunt harmonic filters for low and medium voltage: A cost comparison study", Paper 95 WM 264 PWRD presented at the IEEE/PES Winter Meeting, New York, 1995.

Kellenberger, W.: "Der optimale Winkel die Winkel für die Abstützung von vertikalen Wasserkraftgeneratoren mit schrägen Armen oder Blattfedern", Brown Boveri Mitteilungen, no. 2, 1980.

Kelouwani, S.; Agbossou, K. & Chahine, R.: "Model for energy conversion in renewable energy system with hydrogen storage", Journal of Power Sources, vol. 140, no. 2, pp. 392-399, 2005.

> A dynamic model for a stand-alone renewable energy system with hydrogen storage (RESHS) is developed. In this system, surplus energy available from a photovoltaic array and a wind turbine generator is stored in the form of hydrogen, produced via an electrolyzer. When the energy production from the wind turbine and the photovoltaic array is not enough to meet the load demand, the stored hydrogen can then be converted by a fuel cell to produce electricity. In this system, batteries are used as energy buffers or for short time storage. To study the behavior of such a system, a complete model is developed by integrating individual sub-models of the fuel cell, the electrolyzer, the power conditioning units, the hydrogen storage system, and the batteries (used as an energy buffer). The sub-models are valid for transient and steady state analysis as a function of voltage, current, and temperature. A comparison between experimental measurements and simulation results is given. The model is useful for building effective algorithms for the management, control and optimization of stand-alone RESHSs.

Kemp, R.: "The Lyon line (high-speed trains)", IEE Review, vol. 37, no. 2, pp. 59-63, 1991.

> On 18 May 1990, the world rail speed record rose to 515 km/h during a high-speed test run of a French train a grande vitesse (TGV). The author looks at the French TGV which have now set a world standard in speed, comfort and efficiency using new designs and innovative technology. The power lines, the TGV Atlantique project and the Channel Tunnel are also described.

Kiehne, H.A.: "Battery Technology Handbook", Marcel Dekker, New York, 1989.

Kim, E.; Roh, P. & Kim, J.: "The operation test of 1 MW battery energy storage system in Korea", Proceedings of the IEEE Region 10 Conference, TENCON 99, vol. 2, pp. 899-902, 1999.

> This paper presents the development of 1 MW battery energy storage system (BESS) test facility and real operation. This system consists of lead acid batteries, an AC/DC power conversion system and a monitoring control system. The main items of the operation test are; basic performance test for load leveling and operation test. The operation test is carried out for interconnection performance. The system is connected to the utility system and tested to establish the system technology for load leveling and BESS operation algorithm considering time of use rate and a subsidy for power factor correction.

Kimura, Y. & Yokoyama, T.: "Planning of Reversible Francis Pump-Turbine", Hitachi Review, vol. 22, no. 8, 1973.

Kita, E.; Kuwabara, T. & Bando, A.: "Development of Control Scheme for Adjustable Speed Pumped Storage Unit", The Third Japan-Chine Joint Conference on Fluid Machinery, pp. I-117-I-124, April 1990.

Kita, E.; Bando, A. & Kuwabara, T.: "400 MW Adjustable-Speed Pumped Storage Hydraulic Power Plant", Hitachi Review, vol. 44, no. 1, pp. 55-62, 1995.

Kjellberg, R.: "The Juktan Pumped Storage Station in Sweden", Water Power, vol. 26, no. 7, pp. 251-253, July 1974.

von KleinSmid W.H.: "Operating and maintenance experiences of the world's largest storage battery", Proceedings of the Sixth Annual Battery Conference on Applications and Advances, pp. 59-64, 1991.

The Chino Battery Storage Project is the world's largest storage battery. This $13.5 million research project recently completed its two-year demonstration phase. This is a report of the operating and maintenance experiences of that phase of the program.

Kobi, H.; Terens, L. & Wikström, P.: "Reliability, interfacing and standardization aspects in high power AC drive applications", Proceedings IPC Conference, pp. 1095-1106, 1998.

Kolb, Peneder & Suchenek: "Static Equipment for Gas Turbosets", Brown Boveri Review, vol. 66, no. 2, pp. 104-112, February 1979.

Kordesch, K.V.: "Batteries", Marcel Dekker, New York, 1977.

Korpaas, M.; Holen, A.T. & Hildrum, R.: "Operation and sizing of energy storage for wind power plants in a market system", International Journal of Electrical Power and Energy Systems, vol. 25, no. 8, pp. 599-606, 2003.

This paper presents a method for the scheduling and operation of energy storage for wind power plants in electricity markets. A dynamic programming algorithm is employed to determine the optimal energy exchange with the market for a specified scheduling period, taking into account transmission constraints. During operation, the energy storage is used to smooth variations in wind power production in order to follow the scheduling plan. The method is suitable for any type of energy storage and is also useful for other intermittent energy resources than wind. An application of the method to a case study is also presented, where the impact of energy storage sizing and wind forecasting accuracy on system operation and economics are emphasized. Simulation results show that energy storage makes it possible for owners of wind power plants to take advantage of variations in the spot price, by thus increasing the value of wind power in electricity markets. With present price estimates, energy storage devices such as reversible fuel cells are likely to be a more expensive alternative than grid expansions for the siting of wind farms in weak networks. However, for areas where grid expansions lead to unwanted interference with the local environment, energy storage should be considered as a reasonable way to increase the penetration of wind power.

Kortüm, G. & Bockris, J.O'M.: "Textbook of Electrochemistry", Elsevier, New York, Amsterdam, London, 1951.

Kottick, D.; Blau, M. & Edelstein, D.: "Battery energy storage for frequency regulation in an island power system", IEEE Transaction on Energy Conversion, vol. 8, no. 3, pp. 455-459, September 1993.

Large battery energy storage (BES) facilities may provide significant dynamic operation benefits for electric utilities. One area in which a BES facility could be useful is the frequency regulation requirement. This feature is significantly important for island power systems. The purpose of this paper is to quantify the effects of a 30 MW battery on the frequency regulation in the Israeli isolated power system. The study was performed on a single area model representing the whole power system and containing a first order transfer function that represented the BES performance.

Krahn, R.L.: "Measurements of hydraulic turbine windage and friction losses", AIEE Transactions, vol. 79, pp. 1529-1531, 1960.

Kusko, A. & DeDad, J.: "Stored energy - Short-term and long-term energy storage methods", IEEE Industry Applications Magazine, vol. 13, no. 4, pp. 66-72, 2007.

This paper deals with the short-term and long-term energy storage methods for standby electric power systems. Stored energy is required in uninterruptible standby systems during the transition from utility power to engine-generator power. Various storage methods provide energy when the utility source fails. For batteries in cycling duty, Li-ion and Ni-MH cells are coming into wide use to displace VRLA batteries. For float duty, VRLA and NiCd batteries predominate. Flywheel-generator units are being offered to replace batteries in UPS. Fuel cells require a warm-up time and, hence, are suitable for long-term operation. Ultracapacitors are proposed to replace batteries for short-term discharge. CAED and hydrogen energy storage are suitable for large projects.

Kuwabara, T.; Shibuya, A.; Furuta, H.; Kita, E. & Mitsuhashi, K.: "Design and Dynamic Response Characteristics of 400 MW Adjustable Speed Pumped Storage Unit for Ohkawachi Power Station", IEEE Transactions on Energy Conversion, vol. 11, no. 2, pp. 376-384, June 1996.

Köllensperger, D & Tovar, K.: "Stromrichtermotoren größerer Leistung", Siemens Zeitschrift, vol. 43, pp. 686-690, 1969.

Lachs, W.R. & Sutanto, D.: "Battery storage plant within large load centres", IEEE Transactions on Power Systems, vol. 7, no. 2, pp. 762-767, May 1992.

As a long-term strategy, the installation of numbers of battery storage plants (BSPs) in urban centers would significantly raise power system levels of reliability and security. The first large commercial application of a BSP, the Bewag 8.5/17 MW installation, has been in successful operation since January 1987. A brief history of the Bewag development is provided. There are three important advantages of BSP: there are no environmental difficulties to placing them within urban areas; there is an instantly accessible output of MW and MVAr; and commercial consumers requiring a higher reliability will meet much of the capital cost. Utilities would need to offer tariff incentives to gain an operational control of the BSP. The ability for extremely fast output changes of MW and MVAr outputs, coupled with their energy storage, would make BSPs useful for normal and emergency operation as well as speeding up system restoration.

Lachs, W.R. & Sutanto, D.: "Uncertainty in electricity supply controlled by energy storage", Proceedings of the International IEEE Conference on Energy Management and Power Delivery, EMPD '95, vol. 1, pp. 302-307, 1995.

The hour by hour changes of demand cannot be accurately forecast because consumers are free to switch appliances at any instant. The greatest uncertainty is posed by the peak periods even though they are of short duration and only use a small proportion of daily energy consumption. Sufficient quantities of energy storage could curtail daily peak demand changes so permitting replacement of demand forecasting by more predictable daily energy forecasts. Not only would it eliminate peaking generation and simplify generator scheduling, but it would also produce a single daily tariff and allow easier financial planning for power system development. The electricity supply industry would incur capital and operating expenditures for the entire power network and additional generators of $6000 to $7000 for each kW of peak demand growth. This expense could be avoided by battery energy storage systems which could curtail peak demand at a cost of $2000 per kW so gaining savings of $4 to $5 billion for a period with 1000 MW growth of peak demand.

Lachs, W.R. & Sutanto, D.: "Application of battery energy storage in power systems", Proceedings of International IEEE Conference on Power Electronics and Drive Systems, vol. 2, pp. 700-705, 1995.

The key control elements of power systems are relatively slow mechanical devices, turbogenerator governors, transformer tap changers and circuit breaker contacts. Power system engineers have done a remarkable job developing a highly automated power system control with these constraints. However the evolution of more extensive interconnected power systems has turned the transmission grid into a critical superstructure which is increasingly being disrupted by severe disturbances, causing extensive blackouts. The introduction of power electronics, microprocessors, energy storage and communications technology to supplement the mechanical devices and permit faster responses could provide better emergency control and so extend the capabilities of the existing transmission grid as well as providing savings. The authors describe the application of battery energy storage plants to overcome some of the problems in power system control. They describe lead acid batteries, inverters, load patterns and load control, the versatility of battery storage, and the cost benefits.

Laible, T.: "Die Theorie der Synchronmachine im nichtstationären Betrieb", Springer-Verlag, Berlin, 1952.

Landeau, J. (ed.): "Proceedings of the European Space Power Conference", European Space Agency, Special Publication, ESA SP, Noordwijk, Netherlands, 1989.

This conference proceeding contains 129 papers dealing with space power technology. Topics covered include power systems and subsystems; batteries and fuel cells; power electronics; and photovoltaic generators. All papers are abstracted and indexed individually.

Landhult, H. & Andersson, A.: "Starting the generator/motors units for the Castaic Power Project", Rapport OKG, ASEA, 1970.

Larsen, W.A.; Brinson, E.M.; Hall, R.E. & McKay, H.G. III: "Bad Creek Pumped Storage Project – Duke Power Turns to Pumped Storage to Manage the Peaks and Valleys of the Demand Curve", The Professional Engineer, pp. 9-21, September-October 1986.

Lasseter, R.H. & Jalali, S.G.: "Power Conditioning Systems for Superconductive Magnetic Energy Storage", IEEE Trans. on Energy Conversion, vol. 6, no. 3, pp. 381-387, September, 1981.

Lasseter, R.H. & Jalali, S.G.: "Dynamic Response of Power Conditioning Systems for Superconductive Magnetic Energy Storage", IEEE Trans. on Energy Conversion, vol. 6, no. 3, pp. 388-393, September, 1981.

Laurent, P. & Ruelle, G.: "Progress report of Study Committee No. 17: Generators", Report 11-01, 22nd CIGRE Session, Paris, 1968

Lazarev, G.B. & Kostin, V.N.: "Limitation of switching surges in the starting circuit for large synchronous machines from high-voltage thyristor frequency changers", Soviet Electrical Engineering, vol.62, no. 5, pp. 20-25, 1991.

Startup of large synchronous machines, for example, reversible motors-generators of pumped -storage power plants, generators of gas turbine plants, synchronous compensators, from thyristor frequency changers, which permit a smooth change in rotational speed of the rotor at assigned stator current and ensure accurate automatic synchronization with the network and recuperative braking, has become increasingly common, nearly supplanting all other methods of startup. Here, limitations of surges relative to ground are considered in the startup circuits of large synchronous machines from high-voltage thyristor frequency changers.

LeBreux, M.; Lacroix, M. & Lachiver, G.: "Fuzzy and feedforward control of an hybrid thermal energy storage system", Energy and Buildings, vol. 38, no. 10, pp. 1149-1155, 2006.

A control model for operating a system that stores simultaneously sensible heat from solar and electric energy is proposed. The hybrid thermal energy storage system accumulates solar energy during sunny days and releases it later at night or during cloudy days. It also stores heat from an electric heater during off-peak periods so as to release it later during peak periods. The control model, which makes use of 24-h weather forecasts, comprises two types of controllers: a fuzzy logic controller for estimating the daily amount of thermal electric energy to be stored and a feedforward controller for determining the electricity consumption profile of the heating element during off-peak hours. Results indicate that the proposed control system is far superior to traditional control systems. It maintains a comfortable thermal environment at all times, i.e. the temperature fluctuations are kept within the imposed margins and overheating of the room never occurs. Furthermore, compared to a traditional electric base board heating system, it reduces the electricity consumption for the winter season by 24% and 94% of this electricity is consumed during off-peak hours.

Lee, Sang-Seung; Kim, Young-Min; Park, Jong-Keun; Moon, Seung-Il; Yoon, Yong-Tae: "Compressed Air Energy Storage Units for Power Generation and DSM in Korea", IEEE Power Engineering Society General Meeting, pp. 1-6, 2007.

In this paper, we discuss compressed air energy storage (CAES) units, and reflect on a demand-side management (DSM) technique including six generic load shape objectives in the Korea Electric Power Corporation (KEPCO). The CAES technology has been considered for substitute energy utilization not only in regards to the management of large or small loads but also for use by emergency generators during a power failure. Recently, in the energy storage field, countries with CAES have developed small, medium and large units for storage roles. These units can be used for the dual-purpose applications of supplementary power generation and district heating supply systems. These units have an underground cavern or a modular-type pressurized vessel with large and small, micro containers. The storage and utilization time of the CAES are determined by the power between the lower limit and upper limit by the KEPCO load curve patterns over an entire day.

Lee, T.-Y.: "Operating Schedule of Battery Energy Storage System in a Time-of-Use Rate Industrial User with Wind Turbine Generators: A Multipass Iteration Particle Swarm Optimization Approach", IEEE Transactions on Energy Conversion, vol. 22, no. 3, pp. 774-782, 2007.

This paper presents a new algorithm for the solution of nonlinear optimal scheduling problems. This algorithm is called ldquomultipass iteration particle swarm optimizationrdquo (MIPSO). A new index called ldquoiteration bestrdquo is incorporated into ldquoparticle swarm optimizationrdquo (PSO) to improve solution quality. The concept of multipass dynamic programming is applied to further modify the PSO to improve computation efficiency. The MIPSO algorithm is used to solve the optimal operating schedule of a battery energy storage system (BESS) for an industrial time-of-use (TOU) rate user with wind turbine generators (WTGs). The effects of wind speed uncertainty and load are considered in this paper, and the resulting optimal operating schedule of the BESS reaches the minimum electricity charge of TOU rates users with WTGs. The feasibility of the new algorithm is demonstrated by a numerical example, and MIPSO solution quality and computation efficiency are compared to those of other algorithms.

Lehman, C. et al.: "Asynchronous Starting of Motor-Generators of Pumped Storage Stations: Development of the Water Tank Rotor", Report 11-01, 23rd CIGRE Session, Paris, 1970.

Liaw, C.M.; Chen, T.H.; Chiang, S.J.; Lee, C.M. & Wang, C.T.: "Small battery energy storage system", IEE Proceedings B - Electric Power Applications, vol. 140, no. 1, pp. 7-17, January 1993.

A small battery energy storage (BES) system is proposed. The power circuit of this BES system is simple, since only one current-forced subharmonic PWM switching converter is used. The precise current control is achieved by applying feedforward control. If the utility power is off, the BES system operates in the inverter mode to supply power to the load. A sinusoidal output voltage with low distortion and good regulation is obtained by using instantaneous voltage control and average voltage control techniques. When the utility power recovers, the BES system minimises the power from the utility to the load in the peak load period. Conversely, the power from the BES system is minimised in the medium load period. During the off-peak load period, the utility supplies power to the load and also charges the battery bank. In addition to real power conditioning, the BES system can also compensate the load reactive and harmonic powers.

Liaw, C.M.; Chiang, S.J. & Huang, S.C.: "A three-phase multi-functional battery energy storage system", 20th International IEEE Conference on Industrial Electronics, Control and Instrumentation, IECON '94, vol. 1, pp. 458-463, 1994.

A three-phase multi-functional battery energy storage system (BESS) is designed and implemented in this paper. When the utility power is in normal condition, the proposed BESS can be arranged to shave the peak load or charge the battery bank. In either case, since the load is unbalanced, harmonic and reactive powers can be compensated through the proposed active power filtering control, the power factor is maintained near to unity and the line currents drawn from the utility are balanced and sinusoidal with very low distortion. As a utility power failure occurs, the proposed BESS can immediately supply uninterruptible power to the loads. In this case, an instantaneous control technique is developed to yield good three-phase voltage waveforms. The determination of reactive components, the dynamic modeling and the design of controllers for the proposed BESS are made. Some experimental results are provided to demonstrate the effectiveness of the proposed BESS.

Liaw, C.M. & Chiang, S.J.: "Design and implementation of a single-phase three-wire transformerless battery energy storage system", 25th Annual IEEE Power Electronics Specialists Conference, PESC '94, vol. 1, pp. 410-417, 1994.

This paper presents a single-phase three-wire (1Ø 3w) transformerless battery energy storage system (BESS). Its power circuit is simple, since it consists of only one power converter. It has three legs to provide 1Ø 3w 220/110 V output without using a transformer. For switching control, the BESS is decoupled into differential-mode and common-mode subsystems. Each subsystem has its own inner-loop current-forced switching control mechanism, their current commands at various operating modes are generated by outer-loop controllers. The controllers of differential-mode are designed to control the main voltage (220 V) source, and meanwhile to achieve the desired functions of BESS. As to the common-mode subsystem, its controllers are used to maintain the voltage balance of two subcircuits (110 V circuits) when the utility grid fails, and to keep the current in the neutral line of the utility grid at zero when the utility grid is in a normal condition. The operation principle of the proposed BESS and the design of controllers in various operating modes are described in detail. Some experimental results are provided to show the performance of the proposed BESS.

Liaw, C.M. & Chiang, S.J.: "Design and implementation of a single-phase three-wire transformerless battery energy storage system", IEEE Transactions on Industrial Electronics, vol. 41, no. 5, pp. 540-549, 1994.

This paper presents a single-phase three-wire (1Ø 3w) transformerless battery energy storage system (BESS). Its power circuit is simple, since it consists of only one power converter. It has three legs to provide 1Ø 3w 220/110 V output without the use of a transformer. For switching control, the BESS is decoupled into differential-mode and common-mode subsystems. Each subsystem has its own inner-loop current-forced switching control mechanism; their current commands at various operating modes are generated by outer-loop controllers. The controllers of the differential mode are designed to control the main voltage (220 V) source, while achieving the desired functions of BESS. As to the common-mode subsystem, its controllers are used to maintain the voltage balance of two subcircuits (110 V circuits) when the utility grid fails, and to keep the current in neutral line of utility grid at zero when the utility grid is in normal condition. The operation principle of the proposed BESS and the design of controllers in various operating modes are described in detail. Some experimental results are provided to show the performance of the proposed BESS.

Liaw, C.M.; Jan, L.C.; Wu, W.C. & Chiang, S.J.: "Operation control of paralleled three-phase battery energy storage system", IEE Proceedings - Electric Power Applications, vol. 143, no. 4, pp. 317-322, 1996.

Parallel operation for capacity enlargement of a three-phase battery energy storage system (3Ø BESS) is presented. The proposed paralleled system consists of some inner-loop parallel-connected current-regulated pulse width modulated (CRPWM) converters, a current command distributor and an outer-loop common controller. Every single-module CRPWM 3/spl phi/ converter possesses good current tracking control characteristics, so is easy to parallel connect. The proposed current command distributor receives current commands from the common controller and generates suitable current commands for each paralleled converter module according to the proposed current sharing control strategy. The sophisticated system arrangement of the common controller gives the BESS many power processing functions. When it is connected to the utility grid, it can be arranged to give peak load shaving, active power filtering, power factor and battery charging. In the event of utility failure the BESS can supply uninterrupted power with low distortion sinusoidal voltage waveform to critical loads. Performance of the proposed paralleled BESS at various operating conditions is demonstrated experimentally.

Zhou, L. & Xu, S.: "A self-starting two-speed synchronous generator-motor for pumped-storage power station. Experiment (in Chinese)", Proceedings of the CSEE, vol. 14, no. 1, pp. 57-60, January 1994.

The starting and working characteristics of the simulation machine of a self-starting two-speed salient-pole synchronous generator/motor is investigated by means of experimentation. The results show that this new type of machine based on Professor Xu Shizhang's concept has excellent starting and working performance, and thus validates the feasibility of this self-starting method.

Lin, C.E.; Shiao, Y.S.; Huang, C.-L. & Sung, P.S.: "A real and reactive power control approach for battery energy storage system", IEEE Transactions on Power Systems, vol. 7, no. 3, pp. 1132-1140, August 1992.

A power control method using the power flow concept is described. The authors formulate a new and general control equation for the real-time control of a battery energy storage system (BESS). A control strategy for a BESS to operate in a real power mode and a reactive power mode is discussed. Simulations for a demand-side BESS are presented, together with experiments on operating system set-up in a power laboratory using a real time control implementation. The real and reactive power control of a BESS were tested using a 10 kVA/30 kWh laboratory system. The results illustrate that the proposed method is effective and easy.

Lin, C.E.; Tsai, M.T.; Tsai, W.I. & Huang, C.L.: "Development of a general-purpose demand-side battery energy storage system", Conference Record of the 1995 IEEE Industry Applications Conference, Thirtieth IAS Annual Meeting, IAS '95, vol. 3, pp. 1893-1899, 1995.

This paper presents a design and implementation of battery energy storage system (BESS) for general applications in a demand-side industrial power system. Different control modes for operating BESS to improve demand-side power supply capability are studied. The basic principle using the conventional control method is implemented to accomplish the desired control functions. The proposed methods are proved by both theoretical simulations and experimental test results on a prototype BESS.

van der Linden, S.: "Bulk energy storage potential in the USA, current developments and future prospects", Energy, vol. 31, no. 15, pp. 3446-3457, 2006.

Stored energy can provide electricity during periods of high demand, as currently demonstrated with bulk storage systems such as pumped hydro storage (PHS), which accounts for only 2.5% of the current installed base load in the USA. Sites for future developments have become less available, and environmental siting issues, as well as high costs have stopped further prospects. This paper looks at the potential beyond PHS, with bulk storage systems such as compressed air energy storage (CAES) flow-batteries and 1MW flywheel systems that can provide system stability/support at the grid, substations and distributed level. Current developments in bulk energy storage will be reviewed as well as some storage project developments incorporating wind energy and the impact on base-loaded coal and natural gas fired GT combined cycle plants. The large potential and the economic benefits for energy storage in the US will be examined.

Liu, H. & Jiang, J.: "Flywheel energy storage-An upswing technology for energy sustainability", Energy and Buildings, vol. 39, no. 5, pp. 599-604, 2007.

Flywheel energy storage (FES) can have energy fed in the rotational mass of a flywheel, store it as kinetic energy, and release out upon demand. It is a significant and attractive manner for energy futures 'sustainable'. The key factors of FES technology, such as fly-

wheel material, geometry, length and its support system were described, which directly influence the amount of energy storage and flywheel specific energy. It is very suitable to such applications that involve many charge-discharge cycles and little in the way of long-term storage applications including International Space Station (ISS), Low Earth Orbits (LEO), overall efficiency improvement and pulse power transfer for Hybrid Electric Vehicles (HEVs), Power Quality (PQ) events, and many stationary applications. Design margins, fault protection and containment were considered as three good approaches to solve safety issue. Vacuum enclosures or helium-air mixture gas condition were discussed for solution of windage energy loss. In short, with the aid of new technologies the cost of FES can be lowered and the FES will play a significant role in securing global energy sustainability.

Liu, Tian-Hua; Lin, Chih-Ying; Yang, Jin-Shyr; Chang, Wen-Yao (National Taiwan Institute of Technology, Taipei): "Modeling and performance of a static frequency converter starting a 300 MVA synchronous machine", Electric Power Systems Research, vol. 37, no 1, pp. 45-53, April 1996.

This paper presents a study of the dynamic behaviour of a static frequency converter driving a 300 MVA synchronous generator, which is used in a pumped storage power plant of Taiwan Power Company. The static frequency converter, which consists of a three-phase AC/DC phase converter, a filtering inductance, and a six-step current-source inverter, is used to start a 300 MVA synchronous machine. In this paper, first the mathematical model of the whole system, which consists of a synchronous machine, a static frequency converter, a microprocessor, and sensors, is established. Then, the control method of the static frequency converter based on field oriented control is presented. Next, a filter circuit has been designed to reduce the harmonics of the AC source. By using this filter, the harmonics can be effectively reduced. Finally, some computer simulated and experimental results are shown to verify the theoretical analysis. This paper presents a new direction in the use of advanced power electronic technology to drive a very large synchronous machine.

Leung, K.K. & Sutanto, D.: "Improving power system operations and control utilizing energy storage", Fourth International Conference on Advances in Power System Control, Operation and Management, APSCOM-97, Conf. Publ. No. 450, vol. 2, pp. 626-631, 1997.

This paper describes several control strategies to utilise a modern battery energy storage system (BESS) to provide simultaneous control of both its MW and Mvar outputs to improve power system operation and control with the following objective in mind: ability to absorb harmonics, provide load leveling, provide damping of inter-area oscillations, help in damping transient stability, provide effective and fast control power flow along a transmission line corridor, in many ways acting like flexible AC transmission system (FACTS) devices, provide back-up electricity supply on loss of AC supply very similar to UPS applications and provide active power filtering to meet power quality standards. This work shows that BESS offers an important resource for improving power system control.

Leung, K.K. & Sutanto, D.: "A new topology of a battery energy storage system", Proceedings of the International IEEE Conference on Energy Management and Power Delivery, EMPD '98, vol. 1, pp. 253-258, 1998.

This paper describes a new topology of a battery energy storage system (BESS) that can provide simultaneously fast control of both its MW and MVAr outputs to improve power system operation and control. The proposed BESS topology also provides several other important contributions to the power systems such as active harmonic filtering to meet power quality standards, load leveling, damping of inter-area oscillations, damping of transient stability, effective and fast control of power flow along a transmission line corridor, many of the flexible AC transmission system (FACTS) features, and emergency supply on loss of AC source (very similar to UPS applications). This paper shows that BESS can offer an important resource for improving power system control.

Leung, K.K. & Sutanto, D.: "Using battery energy storage system in a deregulated environment to improve power system performance", Proceedings of the IEEE International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, DRPT 2000, pp. 614-619, 2000.

This paper embodies recent work at the Hong Kong Polytechnic University on the application of energy storage in general and BESS in particular in four areas: control of active and reactive power, load leveling, power quality improvement and power flow controller. The research aims at developing novel strategies for controlling those dynamic problems and investigating the advantages and limitation of BESS for the applications investigated. This paper discusses the hardware configuration and software technologies currently being used to implement some of the above objectives, in particular, the fast control of active and reactive power demand and generation when a BESS is connected to the grid. The proposed three-phase multi-purpose BESS will provide active and reactive power independent of the supply voltage with excellent power quality in terms of its waveform.

Long, L.O.: "Joint Control of Electric Governors for Hydraulic Turbines", IEEE Transactions on Power Apparatus and Systems, vol. PAS-87, no. 9, pp. 1754-1762, September 1968.

Lottes, G.: "Entwurfsprobleme beim Krafthaus von Pumpspeicherwerken", Die Bautechnik, vol. 6, pp. 181-187, 1970.

Lottes, G.: "The Development of European Pumped-Storage Plants", Water Power, vol. 24, no. 1, pp. 22-23, January 1972.

Lottes, G. & Schmidhuber, P.: "Das Leizach-Kraftwerk der Stadt München 1911-1981", Elektrizitätswirtschaft, vol. 81, pp. 139-147, 1982.

Louie, H. & Strunz, K.: "Superconducting Magnetic Energy Storage (SMES) for Energy Cache Control in Modular Distributed Hydrogen-Electric Energy Systems", IEEE Transactions on Applied Superconductivity, vol. 17, no. 2, pp. 2361-2364, 2007.

The proposed energy cache control enables fast compensation of stochastic power fluctuations through the use of Superconducting Magnetic Energy Storage (SMES) connected to the DC bus of Distributed Generation (DG). The term energy cache control is chosen to reflect its analogy to the utilization of the data cache in computers. The SMES provides an energy cache for other types of storage with a higher capacity of energy but also longer response times. Together, the two types of storage provide high controllability over diverse time scales. The SMES so enables the creation of modular DG building blocks which can be readily connected to the network in a plug-and-supply mode. In the developed case study, the SMES is part of a DG unit of a model commercial facility that includes renewable-based electric power generation and a hydrogen-electric conversion and storage plant composed of an electrolyser, a fuel cell, and tanks. It is shown how the cache energy control deals with fast fluctuations of power generation and load that are caused by changing wind and sudden power demands of an elevator, respectively. Through its shock-absorbing role, the energy cache control of the SMES prevents the involved disturbances from propagating over the network interface and makes the DG unit behave as a good citizen in terms of network integration.

Lu, C.-F.; Liu, C.-C. & Wu, C.-J.: "Dynamic modelling of battery energy storage system and application to power system stability", IEE Proceedings - Generation, Transmission and Distribution, vol. 142, no. 4, pp. 429-435, 1995.

A useful and systematic dynamic model of a battery energy storage system (BES) is developed for a large-scale power system stability study. The model takes into account converter equivalent circuits, battery characteristics and internal losses. Both charging mode and discharging mode are presented. The model is expressed in equivalent transfer function blocks, and it can be easily used in dynamic stability analysis of a power system. To examine the dynamic behaviour of the model, applications to the damping of turbogenerator torsional oscillations are performed. Active and reactive power modulation by the BES can be controlled according to system requirements. Eigenvalue analysis and dynamic simulations are performed to demonstrate the damping effect of the BES. .

Lu, C.-F.; Liu, C.-C. & Wu, C.-J.: "Effect of battery energy storage system on load frequency control considering governor deadband and generation rate constraint", IEEE Transaction on Energy Conversion, vol. 10, no. 3, pp. 555-561, September 1995.

Since a battery energy storage system (BES) can provide fast active power compensation, it also can be used to improve the performance of load-frequency control. In this paper a new incremental model of a BES is presented and merged into the load-frequency control of a power system. A comprehensive digital computer model of a two-area interconnected power system including governor deadband and generation rate constraint is employed for a realistic response. Computer simulations show that the BES is very effective in damping the oscillations caused by load disturbances. The BES model is suitable for charging mode and discharging mode operations. Optimization of controller gains is obtained by the second method of Lyapunov.

Lu, S.; Corzine, K.A. & Ferdowsi, M.: "A New Battery/Ultracapacitor Energy Storage System Design and Its Motor Drive Integration for Hybrid Electric Vehicles", IEEE Transactions on Vehicular Technology, vol. 56, no. 4, pp. 1516-1523, 2007.

This paper proposes a new energy storage system (ESS) design, including both batteries and ultracapacitors (UCs) in hybrid electric vehicle (HEV) and electric vehicle applications. The conventional designs require a DC-DC converter to interface the UC unit. Herein, the UC can be directly switched across the motor drive DC link during the peak power demands. The resulting wide voltage variation due to UC power transfer is addressed by the simple modulator that is introduced in this paper, so that the motor drive performance is not disrupted. Based on this new methodology, this paper further introduces two ESS schemes with different topologies, namely 1) UC rating and 2) energy flow control. They are applicable to both lightly and heavily hybridized HEVs. Both schemes have the benefits of high efficiency (without a DC-DC link) and low cost. The simulation and experimental results validate the new methodology.

Lukic, S.M.; Jian Cao; Bansal, R.C.; Rodriguez, F.; Emadi, A.: "Energy Storage Systems for Automotive Applications", IEEE Transactions on Industrial Electronics, vol. 55, no. 6, pp. 2258-2267, 2008.

The fuel efficiency and performance of novel vehicles with electric propulsion capability are largely limited by the performance of the energy storage system (ESS). This paper reviews state-of-the-art ESSs in automotive applications. Battery technology options are considered in detail, with emphasis on methods of battery monitoring, managing, protecting, and balancing. Furthermore, other ESS candidates such as ultracapacitors, flywheels and fuel cells are also discussed. Finally, hybrid power sources are considered as a method of combining two or more energy storage devices to create a superior power source.

Luzzi, A.; Lovegrove, K.; Filippi, E.; Fricker, H.; Schmitz-goeb, M.; Chandapillai, M. & Kaneff, S.: "Techno-Economic Analysis of a 10 MWe Solar Thermal Power Plant Using Ammonia-Based Thermochemical Energy Storage", Solar Energy, vol. 66, no. 2, pp. 91-101, 1999.

The production of solar thermal power on a continuous, 24-h basis is possible by applying thermochemical energy storage. An international group of industrial and academic partners is studying such a base-load solar power plant concept, where the reversible thermo-catalytic ammonia reaction serves as the energy vector between supply and demand. Early results confirm the technical soundness of the concept using conventional technology, equipment and materials, and indicate also the potential for economic viability. A first-of-a-kind, solar-only demonstration power plant with a net capacity of 10 MWe would require a capital investment of the order of AUD 180 million and operate with a net solar-to-electric conversion efficiency of 18% and a capacity factor of 80%. This would result in levelised electricity costs of less than AUD 0.25 per kWh.

Magsaysay, G.; Schuette, T. & Fostiak, R.: "Use of a Static Frequency Converter for Rapid Load Response in Pumped-Storage Plants", IEEE Transactions on Energy Conversion, vol. 10, no. 4, pp. 694-699, December 1995.

Makansi J.: "Energy Storage: Value Is Clear, But Who Will Pay", Power Engineering, vol. 108, no. 8, pp. 10-12, 2004.

No one disputes that energy storage devices have great value to electricity production, delivery, and use, and that commercial technology options across the size spectrum are available today. The challenge to widespread adoption of these devices and systems is getting all the stakeholders who derive the value. Another way of looking at it: The disaggregation of the electricity supply and delivery chain has not been kind to storage. Michael Morris, CEO of the Electricity Storage Association's annual meeting host American Electric Power Corp, offered an optimistic assessment when he kicked off the conference by noting that, in gas storage, utilities kept saying, we do what we do. Perhaps the biggest news at the conference was delivered by Brad Williams, PacifiCorp, Portland, Ore. The flagship demonstration of one of the most important advanced battery technologies, vanadium redox, has been functioning in full power cycling operations since March.

Maly, D.K. & Kwan, K.S.: "Optimal battery energy storage system (BESS) charge scheduling with dynamic programming", IEE Proceedings - Science, Measurement and Technology, vol. 142, no. 6, pp. 453-458, 1995.

A dynamic programming algorithm for the optimal charge/discharge scheduling of BESS energy storage is presented. It ensures the minimisation of the electricity bill for a given battery capacity, while reducing stress on the battery and prolonging battery life. Optimal scheduling of the battery charge state is in itself unique; the methods of multipass dynamic programming are used to accomplish this. Maximum payoff for load redistribution and peak load shaving is determined while accounting for charging rate, battery voltage fluctuation and internal losses as a function of charge state. The optimal charging curve is significantly different from the curve conventionally published for BESS.

Manolakos, D.; Papadakis, G.; Papantonis, D. & Kyritsis, S.: "A stand-alone photovoltaic power system for remote villages using pumped water energy storage", Energy, vol. 29, no. 1, pp. 57-69, 2004.

The present paper regards the implementation of a stand-alone photovoltaic plant in which battery storage is partially replaced by a micro-hydraulic system. The plant was installed on Donoussa Island in the Aegean Sea, Greece to cover basic electricity needs of the remote village of Merssini (13 houses). Lighting, TV set and refrigerator were considered basic electricity needs for each house. The photovoltaic array consists of 300 photovoltaic modules of 60 Wp each, for a combined 18 kWp total installed power. The micro-hydraulic system consists of a water pump of 6 kV A and a water turbine coupled with a DC generator of 7.5 kW and two identical water reservoirs of 150 m3 capacity each. During the day, the load is satisfied directly form the photovoltaic generator through an inverter (UPS unit of 25 kV A, 380 V-3 phases alternative current), while any energy surplus is directed to the pump for pumping water from the low level reservoir (at about 100 m altitude from sea level), to the high level reservoir (at about 200 m altitude from sea level). During the night, water is turbined to the low level reservoir providing energy to the load. There is also a battery bank of 186 cells of 2 V nominal voltage in series, with a total capacity of 100 A h. The batteries cover primarily load peaks. The paper presents first results and experience gained from the system performance.

Mansoor, A.; Grady, W.M., Chowdhury, A.H. & Samotyj, M.J.: "An investigation of harmonics attenuation and diversity among distributed single-phase power electronic load", IEEE Transactions on Power Delivery, vol. 10, pp. 467-473, 1995.

Marchesoni, M. & Vacca, C.: "New DC-DC Converter for Energy Storage System Interfacing in Fuel Cell Hybrid Electric Vehicles", IEEE Transactions on Power Electronics, vol. 22, no. 1, pp. 301-308, 2007.

The use of energy storage devices such as batteries or supercapacitors is almost mandatory in fuel cell hybrid electric vehicles, in order to guarantee load leveling, assuring braking energy recovery and good performances in transient operations. To this end, converters with bidirectional power flows are needed to connect the accumulators to the dc-link of the motor drive system. In this paper, a new conversion structure for the bidirectional interfacing of two dc voltage sources with a higher voltage dc-link is presented, where only three controllable power electronic switches are needed and where the only limit is that the sum of the two dc voltages must be lower or equal than the motor drive dc-link voltage. The analysis of the converter structure, the control and modulation systems that have been developed, and simulations and experimental results are reported

Massie, L.D.: "Space power systems requirements and issues: The next decade", IEEE Aerospace and Electronic Systems Magazine, vol. 5, no. 12, pp. 4-9, December 1990.

Some of the more important space power technology issues, requirements, and challenges of the 1990s are described, and the impact of new component technology on the overall performance of space power systems is assessed. Advanced component, subsystem and system technologies that will significantly affect the performance, reliability, and survivability of next-generation baseload and burst mode space power systems are emphasised. Technology disciplines related to power sources (solar/nuclear and chemical), power conversion, energy storage, power conditioning/distribution and control, and waste-heat acquisition, transport, and rejection are primarily addressed. For some of them, performance trends that can be used as the basis for projecting future advanced power-system performance are developed. Performance capabilities for several different types of space power system for both baseload and burst mode applications are postulated on the basis of evolving technology and point designs that incorporate projections of advanced component capabilities.

McDowall, J.: "Nickel-cadmium batteries for energy storage applications", The Fourteenth Annual Battery Conference on Applications and Advances, pp. 303-308, 1999.

Battery energy storage (BES) is a catchall term describing an emerging market that uses batteries to support the electric power supply. BES may be implemented by an electricity provider or by an end user, and the battery duty cycle may vary considerably from application to application. For example, longer-duration capacity (MWh) availability is a requirement of load leveling, while high performance (MW) is needed for applications such as power quality and spinning reserve. At its low end, this market merges with conventional uninterruptible power supply (UPS) systems. High-end systems employ sophisticated power conversion devices and controllers to interface with the power grid, while nominal battery voltages can be measured in kilovolts. To date, only a handful of high-end systems have been deployed. However, the electric utility segment of this market in the USA is predicted to exceed 500 MW of capacity by 2010, and many more systems are likely to be installed by end users. Technologies that compete with BES include traditional generation methods (combustion turbines and diesels), pumped hydro, compressed air energy storage (CAES), superconducting magnetic energy storage (SMES), supercapacitors, flywheels, and fuel cells. This paper describes the various BES applications, and details how nickel-cadmium (Ni-Cd) batteries can provide particular benefits in many cases. The conclusion is that, despite its high initial cost, the Ni-Cd option often has the lowest cost of ownership, or life cycle cost.

McDowall, J.: "Integrating energy storage with wind power in weak electricity grids", Journal of Power Sources, vol. 162, no. 2, pp. 959-964, 2006.

Energy storage is required to match wind generation to consumption. This time shifting can be accomplished with several hours of storage, but studies have shown that the economic value of such storage systems is unlikely to support their widespread use. This does not mean that the outlook is uniformly bleak for storage with wind power. This paper discusses storage systems ranging from a few seconds of run time to several hours, and provides a rationale for the use of systems with several minutes of run time to support a high penetration of wind power into weak electricity grids.

McEarchern, A.; Grady, W.M.; Moncrief, W.A.; Heydt, G.T. & Mc Granaghan, M.: "Revenue and Harmonics: An Evaluation of Some Proposed Rate Structures", IEEE Transactions on Power Delivery, vol. 10, pp. 474-482, 1995.

McLaren, D.G.; Herrin, R.C. & Wright, R.H.: "Design Feaures of the Bad Creek Pumped Storage Project Generator Motors", IEEE Transactions on Energy Conversion, vol. 4, no. 2, June 1989.

Meir, W.; Baumann, K.MJ. & Randegger, E.. "Das Anfahren von Speicherpumpen", IAHR-AIRH-Symposium, 1968.

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de Mello, F.P. & Rustebakke, H.M.: "Random paralleling of aircraft alternators", AIEE Transactions (Applications and Industry), vol. 77, pp. 322-330, 1958.

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Metcalf, E.T.: "Reversible generator/motors for pumped storage application", English Electrical Journal, vol. 18, no. 5, pp. 30-44, 1963.

Metcalf, E.T.: "Reversible generator/motors for pumped storage application", English Electrical Journal, vol. 18, no. 6, pp. 19-23, 1963.

Meyer, H.G.: "Static frequency changers for starting synchronous machines", Brown Boveri Review, vol. 51, no. 8/9, pp. 526-530, August/September 1964.

Meyers, J.F. & Armbruster, T.F.: "Semi-Synchronous Starting", Allis-Chalmers Engineering Review, vol. 33, no. 3, pp. 4-7, 1968.

Miller, D.J., Murray, A.T.L., Marshall, C.C. & Argent, G.G.R.: "Foyers pumped-storage project", Proceedings IEE, vol. 122, no. 11, pp. 1222-1234, November, 1975.

Miller, N.W.; Zrebiec, R.S.; Delmerico, R.W. & Hunt, G.: "Battery energy storage systems for electric utility, industrial and commercial applications", Eleventh Annual IEEE Battery Conference on Applications and Advances, pp. 235-240, 1996.

> Voltage depressions and power interruptions are rapidly becoming two of the hottest topics in the field of power quality. Of particular interest is the need to supply a dependable, efficient and controllable source of real and reactive power, which is available instantly to support a large (<0.5 MVA) load, even if the utility connection is lost. This paper describes a versatile solution to this problem for utility, industrial and commercial applications using battery energy storage systems (BESS). BESS have the potential to provide other substantial benefits in terms of improved voltage and energy management in conjunction with this protection from interruptions.

Miller, N.W.; Zrebiec, R.S.; Delmerico, R.W.; Hunt, G. & Achenbach, H.A.: "A VRLA battery energy storage system for Metlakatla, Alaska", Eleventh Annual IEEE Battery Conference on Applications and Advances, pp. 241-248, 1996.

> The emergence of new power electronics and improved battery technology has created renewed interest in battery energy storage systems (BESS). These new systems provide electric utilities with alternatives to conventional storage technologies, such as pumped hydro. BESS has the potential to provide substantial benefits in terms of energy management, improved voltage, spinning reserve and protection from interruptions when compared to large centralized storage. This paper describes a commercial, economically justified, application of the new BESS which is under construction in the Metlakatla Power and Light system. The paper outlines the system performance requirements which lead to consideration of BESS as an option; the economic factors which provided the justification for BESS as an economic alternative; and the overall BES system design and performance.

Miller, N.W.; Zrebiec, R.S.; Hunt, G. & Deimerico, R.W.: "Design and commissioning of a 5 MVA, 2.5 MWh battery energy storage system", Proceedings of the IEEE Transmission and Distribution Conference, pp. 339-345, 1996.

Momentary and sustained power interruptions are some of the most difficult and important power quality problems facing many industrial and commercial users. Battery energy storage systems (BESS) have the potential to provide versatile solutions to this problem for utility, industrial and commercial applications. This paper describes the design and commissioning of a 5 MVA, 2.5 MWh BESS which is now in operation at the GNB Battery Recycling Plant in Vernon, California. The BESS at Vernon provides the required power combined with both voltage and frequency control to allow the plant to tolerate disconnection from the utility grid without suffering unacceptable impacts on critical loads.

Miller, N.W.; Zrebiec, R.S.; Delmerico, R.W. & Hunt, G.: "Design and commissioning of a 2.5 MWh battery energy storage system"14th International Conference and Exhibition on Electricity Distribution, CIRED, Part 1: Contributions, IEE Conf. Publ. No. 438, vol. 2, pp. 10/1-10/5, 1997.

Momentary and sustained power interruptions are one of the most difficult and important power quality problems facing many industrial and commercial users. A particularly challenging problem is the need to supply an economical, dependable, efficient and controllable source of real and reactive power, which is available instantly to support a large (<1.0 MW) load, if the electric utility connection is lost. Battery energy storage systems (BESS) have the potential to provide versatile solutions to this problem for utility, industrial and commercial applications. This paper describes the design and installation a 5 MW peak, 2.5 MWh BESS which is now in commercial operation at the BNG Battery Recycling Facility in Vernon, California, USA. Results of commissioning tests are discussed. The BESS at Vernon provides the required power combined with both voltage and frequency control necessary to allow the Vernon facility to tolerate disconnection from the electric utility grid without suffering unacceptable impacts on critical loads.

Milton, R.M. & Leech, H.H.: "Tennessee Valley Authority's 500-kV System Step-Down Substation Design", IEEE Transactions on Power Apparatus and Systems, vol. PAS-85, no. 1, pp. 36-46, January 1966.

Minato, ? & Sanematsu, ?: "Development of variable speed pumped storage systems", Journal of the Institute of Electrical Engineers of Japan, vol. 107, p. 205, 1987.

Minkov, V., Krumpelt, M., Daniels, E.K., Asbury, J.G. & Zeh, C.M.: "Evaluation of Fuel Cell Technologies for Electric Utility Applications", ANL/PPRNT-89-188, Argonne National Lab., 1989.

The purpose of this article is to discuss the applicability of baseload fuel cell systems to electric utilities by comparing the technical and economic performance of contemporary power systems, such as the combined cycle and pulverized coal plants, to the performance of ''traditional'' and optimized fuel cell systems. Before going into the substance of that discussion, the fuel cell technology is briefly described.

Newman, J.S.: "Electrochemical Systems", Second Edition, Prentice-Hall, Englewood Cliffs, 1993.

Mock, C.H.: "Electrical Features of Racoon Mountain Pumped-Storage Pant", Paper T 72 233-0, presented at the IEEE/PES Winter Meeting, January 30 – February 4, 1972.

Mock, C.H.: "Electrical Features of Racoon Mountain Pumped-Storage Pant", IEEE Transactions on Power Apparatus and Systems, vol. PAS-91, pp. 1875-1880, 1972.

Molina, M.G.; Mercado, P.E. & Watanabe, E.H.: "Static synchronous compensator with superconducting magnetic energy storage for high power utility applications", Energy Conversion and Management, vol. 48, no. 8, pp. 2316-2331, 2007.

Power systems security in the case of contingencies is ensured by maintaining adequate ''short-term generation reserve''. This reserve must be appropriately activated by means of the primary frequency control (PFC). Because the generation is an electro-mechanical process, the primary control reserve controllability is not as fast as required, especially by modern power systems. Since the new improvements achieved on the conventional control methods have not been enough to satisfy the high requirements established, the necessity of enhancing the performance of the PFC has arisen. At present, the new energy storage systems (ESS) are a feasible alternative to store excess energy for substituting for the primary control reserve. In this way, it is possible to combine this new ESS with power converter based flexible ac transmission systems (FACTS). This allows an effective exchange of active power with the electric grid and, thus, enhances the PFC. This paper presents an improved PFC scheme incorporating a static synchronous compensator (STATCOM) coupled with a superconducting magnetic energy storage (SMES) device. A detailed full model and a control algorithm based on a decoupled current control strategy of the enhanced compensator are proposed. The integrated STATCOM/SMES controller topology includes three level, multi-pulse, voltage source inverters (VSI) with phase control and incorporates a two quadrant, three level, dc-dc chopper as the interface between the STATCOM and the SMES coil. A novel three level control scheme is proposed by using concepts of instantaneous power in the synchronous rotating d-q reference frame. The dynamic performance of the presented control algorithms is evaluated through digital simulation performed by using SimPowerSystems of SIMULINK/MATLAB(TM), and technical analysis is performed to obtain conclusions about the benefits of using SMES devices in the PFC of the electric system. Presently, a laboratory scale prototype device based on digital signal processors (DSP) is being implemented.

Mollersten, K.; Gao, L.; Yan, J. & Obersteiner, M.: "Efficient energy systems with CO2 capture and storage from renewable biomass in pulp and paper mills", Renewable Energy, vol. 29, no. 9, pp. 1583-1598, 2004.

This paper investigates the impact of combining CO2 capture and storage with alternative systems for biomass-based combined heat and power production (CHP) in Kraft pulp and paper mills. We compare heat, power, and CO2 balances of systems with alternative configurations of the CHP and CO2-capture systems. Because the captured CO2 comes from renewable biomass, the studied systems yield negative CO2 emissions. It is shown that pulp mills and integrated pulp and paper mills have the potential to become net exporters of biomass-based electricity while at the same time removing CO2 from the atmosphere on a net basis. The study shows that that the overall best CO2 abatement is achieved when CO2 capture is carried out within a biomass integrated gasifier with combined cycle where the syngas undergoes a CO-shift reaction. This configuration combines efficient energy conversion with a high CO2 capture efficiency. Furthermore, cost curves are constructed, which show how the cost of CO2 capture and storage in pulp and paper mills depends on system configuration and the CO2 transportation distance.

Molokáč, Š.; Grega, L.; Rybár, P.: "MRI device – alternative for electrical energy storage", Metalurgija, vol. 47, no. 1, pp. 65-682008.

It is well known, that the electrical energy storage in the large scale is basically difficult process. Such a process is marked by the energy losses, as the conversion of electrical energy into another form, is most frequently for example mechanical, and then back to the primary electrical form. Though, the superconducting magnetic energy storage (SMES) technology offers the energy storage in an unchanged form, which is advantageous primarily in the achieved efficiency. Magnetic resonance imaging (MRI) devices, commonly used in the medical facilities are based on the application of superconducting magnet. After its rejection from operation, there is possibility of using such devices for energy storage purposes. Additionally, such a technology of storage is also ecological.

Montesano, J.J. & Osburn, G.D. (US Bureau of Reclamation, Denver): "Static starting system replacement at Mt. Elbert pumped storage powerplant", IEEE Transactions on Energy Conversion, vol. 12, no. 1 pp. 66-72, March 1997.

This paper describes the replacement of a static starting system at the US Bureau of Reclamation's Mt. Elbert pumped-storage power plant, near Leadville, Colorado, USA. Problems with the previous static starter are described and design criteria for the replacement system are discussed. Installation issues and testing experience are included. Operating experience, training and manufacturer's support is also discussed.

Morita, M., Miyasaka, K., Uenosono, C., Umezu, T., Kaminosono, H. & Hano, I.: "Synchronous starting of large generator-motors in pumped storage hydro plants", Report 131, 21st CIGRE Session, Paris, 8 June - 18 June, 1966.

Moseley, P.T.: "Energy storage in remote area power supply (RAPS) systems", Journal of Power Sources, vol. 155, no. 1, pp. 83-87, 2006.

Preliminary cost analyses indicate that hybrid RAPS systems are more economically attractive as a means to provide electricity to remote villages than are alternatives such as 24h diesel generation. A hybrid remote area power supply (RAPS) system is being deployed to provide 24h electricity to villages in the Amazon region of Peru. The RAPS system consists of modules designed to provide 150kWh per day of utility grade ac electricity over a 24h period. Each module contains a diesel generator, battery bank using heavy-duty 2V VRLA gelled electrolyte batteries, a battery charger, a photovoltaic array and an inverter. Despite early difficulties, the system in the first village has now commenced operation and the promise of RAPS schemes as a means for providing sustainable remote electrification appears to be bright.

Moubray, J.: "Reliability-Centred Maintenance", Butterworth-Heinemann, Oxford, 1991.

Murphy, D.J.; Bogdovitz, W.J. & Hernandez, N.M.: "Rocky Mountain Project Overview", Proceedings of the International Conference on Hydropower, vol. 3, pp. 1636-1645, July 24-26 1991.

Murphy, J.M.D. & Turnbull, F.G.: "Power Electronic Control of AC Motors", Pergamon Press, Oxford, 19??.

Mühlemann, E.H.: "Arrangements of Hydraulic Machines for Pumped Storage and Comparison of Cost Efficiency and Starting Time", Escher Wyss News, no. 1, pp. 3-11, 1972.

Mühlocker, H.; Senne, H. & Stapelberg, W.: "Entwurf der elektrischen Ausrüstung des Pumpspeicherwerkes Waldeck II", Elektrizitätswirtschaft, vol. 72, pp. 154-161, 1973.

Naganuma, S., Hachiya, T.,Tanikoshi,T. & Yamabe, M.: "Single-stage, 500 m High-head Reversible Pump-turbines and Generator-motors for Numappara Power Station", Hitachi Review, vol. 20, no. 7, pp. 286-293, July 1971.

Nakamura, ? et al.: "Application of adjustable speed pumped storage system", Journal of the Institute of Electrical Engineers of Japan, vol. 111-B, p. 583, 1991.

Nakazawa, S. & Tokuda, T.: "Making Turbine-Generators Do Double Duty", Electric Journal, vol. 28, p. 469, August 1931.

Nickle, C.A. & Pierce, C.A.: "Stability of synchronous machines – effect of armature circuit resistance", AIEE Transactions, vol.49, pp. 338-350, 1930.

Nitta, S. & Yokoyama, T.: "Design, Manufacturing and Field Test Results of 318 000 kW Pump Turbines for the Nabara Power Station, Chugoku Electric Power Co.", Hitachi Review, vol. 26, no. 3, pp. 103-109, 1977.

Nomura, S.; Hagita, T.; Tsutsui, H.; Sato, Y &; Shimada, R.: "Interconnected power systems with superconducting magnetic energy storage", Electrical Engineering in Japan, vol. 164, no. 2, pp. 37-43, 2008.

The objective of this work is to discuss the concept of back-to-back interconnection systems with energy storage, especially with a Superconducting Magnetic Energy Storage (SMES) incorporated into a back-to-back DC link. In this case, each converter of the back-to-back system is used as a power conditioning system for the SMES coils. Since the AC-DC converter can be designed independently of the frequency of the power system, a two-way switch is connected to the AC side of each converter. This two-way switch can select the interconnected power systems. By using the two-way switches, this system can provide the stored energy in the SMES system to each interconnected power system through two AC-DC converters. For instance, lower-cost power of each power network can be stored through two converters during the off-peak hours and made available for dispatch to each power network during periods of demand peak. Then this system increases the reliability of electric power networks and enables the economical operations depending on the power demand. This paper describes the unique operations of the back-to-back interconnection with SMES and discuses the optimal SMES configuration for a 300-MW-class back-to-back interconnection.

Nonaka, S.: "A utility-connected residential PV system adapted a novel single-phase composite PWM voltage source inverter", Record of the Twenty Fourth Photovoltaic Energy Conversion Conference; IEEE Photovoltaic Specialists Conference, vol. 1, pp. 1064-1068, 1994.

An electric utility-interactive residential PV power system adapted novel single-phase composite PWM voltage source inverter (VSI) is proposed. The proposed system is equipped with PV array, battery storage, and a single-phase VSI, which has a new circuit configuration and PWM method. The VSI circuit consists of the normal single-phase bridge circuit and an additional arm. The two auxiliary self-turn-off devices of the arm avail to adopt a composite PWM control, which contributes to reduce the ripple in the AC output current. Also, the VSI has a LC series resonance circuit tuned to twice the utility frequency connected in parallel with the smoothing capacitor. The series resonance circuit absorbs the double-frequency AC components included in the DC pulsated current. Consequently, the smoothing capacitor is drastically reduced. It was found by computer simulation and experiment that the waveform of AC output current shows an ideal sine wave.

Nwachukwu, N.P. & Okonkwo, W.I.: "Effect of an Absorptive Coating on Solar Energy Storage in a Thrombe wall system", Energy and Buildings, vol. 40, no. 3, pp. 371-3742008.

An analysis is undertaken to show the effects of a range of coating absorptivity values on the improvement of heat transfer across a Trombe wall (which is used for passive solar heating) and to its enclosure. The analysis shows that enhanced heat delivery to the enclosure of a Trombe wall system is feasible with the application of an absorptive coating of a superior nature - characterized by high absorptivity and very low emissivity - on the heat-receiving surface of the wall and thus can be seen as a heat transfer enhancement technique.

Okuno, T.; Ujiie, R. & Yanagiya, Y. (Fuji Electrical Company, Tokyo): "Results of field test of large generator and static converter starting system (for Palmiet pumped storage power station)", Fuji Electric Review, vol. 36, no. 2, pp. 77-79, 1990.

Fuji Electric have delivered two 250 MVA generator-motors for 203.5 MW Francis type pump turbines for the Palmiet pumped storage power station. The generator-motors for the Palmiet pumped storage power station concentrate on using new technology. Their main features are the use of the static converter starting system and adoption of a DDC (direct digital control) system as its controller. The authors discuss the field test results of the generator and convertor starting.

Oliver, J.A. & Samotyj, M.J.: "Lessons Learned From Field Tests of Large Induction Motor Adjustable Speed Drives", Report 11-303, CIGRE Session, Paris, 26th August 1st September 1990.

Osburn, G.D. & Atwater, P.L. (US Bureau of Reclamation, Denver): "Design and Testing of a Back-to-Back Starting System for Pumped Storage Hydrogenerators at Mt. Elbert Powerplant", IEEE Transactions on Energy Conversion, vol. 7, no. 2, pp. 280-288, June 1992.

The design and testing of a back-to-back starting system for pumped storage hydrogenerators is described. Marginal reliability of the existing static starting system adversely affected availability of the two 170 000 hp pumps. An alternative method of starting a unit in the pump mode was needed to increase plant availability and to provide interim starting capability for a planned static starter replacement. A back-to-back starting system that allows one unit, operating in generating mode, to synchronously start the other unit as a motor was designed. Field-testing demonstrated the viability of back-to-back starting of the pumped storage units.

Oudalov, A.; Chartouni, D.; Ohler, C. & Linhofer, G.: "Value Analysis of Battery Energy Storage Applications in Power Systems", IEEE PES Power Systems Conference and Exposition, pp. 2206-2211, 2006.

Stressed and less secure power system operating conditions have encouraged both power utilities and large power consumers to look for bulk energy storage systems. Battery energy storage systems (BESS) have excellent records and are used for decades in power systems. This paper describes a methodology for a monetary value analysis of the BESS for load leveling, control power and peak shaving applications. The purpose of this value analysis is to highlight the application with the highest financial benefit for the owner of the BESS. To determine the overall economic viability, revenue of each application has been compared with capital and operating costs over the BESS lifetime. The results of the value analysis show that primary control power is the application that most likely will be asked for by utilities during next 3-5 years.

Oudalov, A.; Chartouni, D. & Ohler, C.: "Optimizing a Battery Energy Storage System for Primary Frequency Control", IEEE Transactions on Power Systems, vol. 22, no. 3, pp. 1259-1266, 2007.

This paper presents a method for the dimensioning of a battery energy storage system (BESS) to provide a primary frequency reserve. Numerical simulations based on historic frequency measurements are used to determine the minimum possible capacity, i.e., the lowest possible cost, which fulfills the technical requirements of the grid code. We implement a novel control algorithm with adjustable state of charge limits and the application of emergency resistors. At current European market prices, an optimized lead-acid BESS can be a profitable utility solution for the primary frequency control.

Paciura, K.; Hancke, G.P.; Grzesiak, L.; Koczara, W. & De Ponte, M.: "A battery energy storage system for the Hygen electricity generator and power supply system", 1999 IEEE Africon, vol. 2, pp. 949-954, 1999..

Batteries are the Achilles' heel in power supply systems, which include energy storage through series connected battery strings. Even though the duty cycles of batteries in UPS applications are the least troublesome, in mission critical UPS applications batteries are replaced prematurely to guarantee reliability. In hybrid electric vehicles and the Hygen application, batteries are subjected to abusive operating conditions and severe duty cycles. Popular batteries and established battery management systems have proved to be unreliable. An energy storage system, utilizing advanced lead-acid batteries and a special battery monitoring and control system, was developed for the Hygen application.

Paksoy, H.O.; Andersson, O.; Abaci, S.; Evliya, H. & Turgut, B.: "Heating and cooling of a hospital using solar energy coupled with seasonal thermal energy storage in an aquifer", Renewable Energy, vol. 19, no. 1-2, pp. 117-122, 2000.

A system is being designed, using solar energy in combination with Aquifer Thermal Energy Storage (ATES), that will conserve a major part of the oil and electricity used for heating or cooling the Cukurova University, Balcali Hospital in Adana, Turkey. The general objective of the system is to provide heating and cooling to the hospital by storing solar heat underground in summer and cold in winter. As the main source of cold energy, ventilation air at the hospital and surface water from the nearby Seyhan Lake will be used.

Papic, I.: "Simulation model for discharging a lead-acid battery energy storage system for load levelling", IEEE Transaction on Energy Conversion, vol. 21, no. 2, pp. 608-615, 2006.

> A battery energy storage system (BESS) stores energy at lower demand and sends saved energy back to the system during peak load. It thus represents a good solution for daily load leveling. The evaluation of the Ampere-hour capacity of the battery needed for load leveling during a period of several hours is of great importance when using BESS as an active power peaking station. A battery simulation model that was developed for this purpose is presented in the paper. The model takes into account the battery voltage dependency on the capacity and current, and is based on the performed battery measurements at constant discharging currents. By using this model, which should prove to be a very effective tool for BESS capacity planning, the simulation of the characteristic load leveling was performed and compared to the measured voltage and current profiles.

Park, R.H.: "Two-Reaction Theory of Synchronous Machines. I. Generalized Method of Analysis", AIEE Transactions, vol. 48, pp. 716-730, July 1929.

Park, R.H.: "Two-Reaction Theory of Synchronous Machines ", AIEE Transactions, vol. 52, pp. 352-354, 1933.

Parker, C.D.: "Lead-acid battery energy-storage systems for electricity supply networks", Journal of Power Sources, vol. 100, no. 1-2, pp. 18-282001.

> This paper examines the development of lead-acid battery energy-storage systems (BESSs) for utility applications in terms of their design, purpose, benefits and performance. For the most part, the information is derived from published reports and presentations at conferences. Many of the systems are familiar within the energy-storage community; others have appeared in numerous tabulations of such systems, but little is known about them beyond the basic descriptive parameters such as energy and power ratings. As a consequence, some are simply cited without comment while others are described in appreciable detail. It is found that a progression in the maturity and applications of battery energy-storage is evident in these systems.

Patel, G. & Deckman, J.T.: "Replacement of the static frequency converter starting equipment at the Raccoon Mountain Pumped Storage Plant", Proceedings of Waterpower 1995 – The International Conference on Hydropower, San Francisco, 25 July 1995-28 July 1995, vol. 2, pp. 1510-1515, 1995.

> In October 1994, the Tennessee Valley Authority awarded a contract for replacement of their Static Frequency Converter (SFC) Starting Equipment at the Raccoon Mountain Pumped Storage Plant. Replacement of the original SFC was deemed necessary to counter a rising forced outage rate and costly repairs directly attributable to the advanced age and condition of the original equipment. This paper presents a comparison of the features of the new SFC versus the original SFC. The new SFC is scheduled to undergo checkout and testing in spring of 1996.

Pavelka, J.: "Special Questions of Project and Operation Experiences with Large Power Converter Variable Speed Drives", Report 11-301, CIGRE Session, Paris, 26th August 1st September 1990.

Peeran, S.M. & Cascadden, C.W.P.: "Application, design and specification of harmonic filters for variable frequency drives", IEEE Transactions on Industry Applications, vol. 31, pp. 841-849, 1995.

Peneder, F. & Butz, H.: "Erregersysteme für Drehstrom-Generatoren in Industrie- und mittleren Kraftwerken", Brown Boveri Mitteilungen, vol. 61, no. 1, pp. 41-50, 1974.

Peneder, F. & Herzog, H.: "Modern excitation equipment for hydro-electric generators", Brown Boveri Review, vol. 67, no. 2, pp. 141-151, 1980.

Peneder, F. & Suchanek, V.: "Static frequency changers for driving and running up high-power synchronous machines", Brown Boveri Review, vol. 67, no. 9, pp. 524-529, September 1980.

Peterson, H.A.; Mohan, N. & Bloom, R.W.: "Superconductive Energy Storage Inductor - Converter Units for Power Systems", IEEE Transactions on Power Apparatus and Systems, vol. 94, no. 4, pp. 1337-1348, July/August 1975.

Petersson, T.: "Elektriska startmetoder för reversibla pumpkraftaggregat", Tekniskt meddelande 11249, FKH, ASEA, 1971-03-29.

Peterson, T.: "Starting Methods for Reversible Pumped-Storage Generator/Motors", Electrical Review, pp. 655-657, 12th May 1972.

Petersson, T.: "Starting Methods for Reversible Pumped-Storage Generator/Motors", ASEA Journal, vol. 46, no. 6, pp. 143-146, 1973.

Petersson, T. & Frank, K.: "Starting of Large Synchronous Motors Using Static Frequency Converter", Paper 71 TP 519-PWR, presented at the IEEE/PES Summer Meeting, Portland, July 18-23, 1971.

Petersson, T. & Frank, K.: "Starting of Large Synchronous Motors Using Static Frequency Converter", IEEE Transactions on Power Apparatus and Systems, vol. PAS-91, no. 1, pp. 172-179, January/February 1972.

Pfafflin, G.E.: "The Coo-Trois Ponts pumped-storage station", Water Power, pp. 43-51, 1970.

Pfister, E. & Press, H.: "Experience in the Construction and Operation of Large Pumped Storage Stations", Paper presented to the 7th World Power Conference, Moscow, 1968.

Phillips, G.A.; Walton, J.W. & Kornbrust, F.J.: "Progress in Self-Commutated Inverters for Fuel Cells and Batteries", IEEE Transactions on Power Apparatus and Systems, vol. PAS-98, no. 4, pp. 1466-1475, July 1979.

> Work has continued on development of large self- commutated inverters for commercial fuel cell applications resulting in successful on-line demonstration with a 1 MW fuel cell pilot plant. Predicted performance was achieved with excellent operating characteristics including delivery of leading or lagging vars within the inverter rating. These results are presented herein. In addition, work was initiated under sponsorship of the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE) to adapt this technology to utility energy storage with advanced batteries now under development and intended for use starting in the late 1980's. Reversible operation without polarity switching has been demonstrated.

Piper, W.-D.: "Der Entwurf des Krafthauses Pumpespeicherwerk Leitzach I (neu) der Stadtwerke Elektrizitätswerke München", Elektrizitätswirtschaft, vol. 83, no. 5, pp. 198-208, 27 February, 1984.

Pouliquen, J.-L.; Teissier, D. (Cegelec Dei, Belfort, France): "The starting of large synchronous machines by static frequency convertor(in French)", Revue Generale de l'Electricite, no. 6, pp. 92-96, June 1992.

> Starter motors for synchronous machines have been steadily renounced in favour of static frequency convertors, which ensure starts at increasing frequency. The authors describe the circuits adopted in various instances and give three examples of applications: an 18 MW convertor working at the voltage (16.5 kV) of the machine, a lower-voltage convertor, and starters for the Gennevilliers power station gas turbine.

Powell, B.K.; Bailey, K.E. & Cikanek, S.R.: "Dynamic Modeling and Control of Hybrid Electric Vehicle Powertrain Systems", IEEE Control Systems, pp. 17-33, October 1998.

Price, A.: "The future of energy storage in a deregulated environment", IEEE Power Engineering Society Summer Meeting, vol. 3, pp. 1523-1526, 2000.

> Energy storage is now a viable option for generation planning. It is a disruptive technology, which is capable of altering the present and established methods of power system planning and operation. The ability to generate electrical power and store the energy for seconds, minutes or hours until required means that power systems no longer have to be configured with sufficient rotating generating plant to meet the peak demand and operating margin. Power plants do not have to be kept in reserve to provide system support (spinning reserve or short-term standby) which is costly in terms of both energy and emissions, it is now possible to install generating plant to meet the average demand, and modulate the supply of electricity using energy storage. Generating plant will be run at optimum conditions in respect of heat rate or efficiency, and emissions. This strategy will lead towards the achievement of two important goals: reducing system operating costs and reducing the environmental impact of power production.

Pröll, E.: "Partial-frequency starting of large synchronous machines, studied with the aid of an analogue computer", Brown Boveri Review, vol. 54, no. 9, pp. 630-637, September, 1967.

Qian, C. & Crow, M.L.: "A cascaded converter-based StatCom with energy storage", IEEE Power Engineering Society Winter Meeting, vol. 1, pp. 544-549, 2002.

> Due to their advantages in high power applications, multi-level converters have been introduced to flexible AC transmission systems (FACTS) to enhance power transmission system operation. Although several multi-level StatCom topologies have been proposed to verify the high performance of multi-level converters used in reactive power compensation, they are not capable of controlling active power flow. To make multi-level converters more flexible and effective for active power flow control, energy storage systems, such as flywheels and batteries are incorporated into StatComs. In this paper, battery energy storage systems (BESS) are incorporated into a cascaded converter-based StatCom to implement both active and reactive power flow control using a PQ-decoupled PI control strategy. Furthermore, the dynamics of the integrated system in damping power oscillations are studied using an electromagnetic transient program PSCAD/EMTDC. Simulation results are provided to verify the feasibility and practicality of these ideas.

Rand, D.A.J. et.al.: "Development of Lead/acid Battery for Domestic Remote-Area Power Supplies", J. Power Sources, vol. 23, pp. 233-, 1988.

Rashid, M.H.: "Power Electronics: Circuits, Devices, and Applications", Prentice-Hall, Englewood Cliffs, 1988.

Reismann, W.: "Die Hohlraumbauten für das Pumpspeicherwerk Waldeck II", Baumasch. u. Bautech., vol. 20, pp. 457-467, 1973.

Rescher, O.J.; Abraham, K.H.; Bräutigam, F. & Pahl, A.: "Ein Kavernenbau mit Ankerung und Spritzbeton unter Berücksichtigung der geomechanische Bedingungen", Rock Mechanics, Supplenet 2, pp. 313-354, 1973.

Richter, E.: "Der Entwurf des Pumpspeicherwerkes Waldeck II", Elektrizitätswitschaft, vol. 71, pp. 149-158, 1972.

Richter, E.: "Kavernen-Pumpenspeicherwerk Waldeck II", Siemens-Zeitschrift, vol. 49, no. 1, pp. 9-14, January 1975.

Ridley, G.K.: "Site testing of large hydro-electric AC synchronous machines", AEI Engineering, vol. 6, pp. 286-297, 1966.

Robertson, L.M.: "The design and construction of Cabin Creek pumped-storage hydroelectric project", Paper presented at the ASME/IEEE Joint Power Generation Conference, September 18- 22, Denver, 1966.

Robertson, L.M. et al.: "Colorado high-altitude corona tests. Parts I-III", AIEE Transactions (Power Apparatus and Systems), vol. 76, pp. 357-376, June 1957.

Robertson, L.M. et al.: "Leadville high-altitude extra-high-voltage test projects. Parts I-IV", AIEE Transactions (Power Apparatus and Systems), vol. 80, pp. 715-748, December 1961.

Robertson, L.M. et al.: "Leadville high-altitude EHV test project – single conductor tests", AIEE Transactions (Power Apparatus and Systems), vol. 81, pp. 939-944, 1962 (February 1963 Section).

Robertson, L.M.; Burt, L.S.; Eastom, F.W.; Hubbard, C.W.; Brennan, F.L.; Fuller, J.F. & Johrde, P.S.: "Electrical Design and Testing of Cabin Creek Pumped-Storage Hydroelectric Project", IEEE Transactions on Power Apparatus and Systems, vol. PAS-87, no. 3, pp. 844-854, March 1968.

Rodriguez, G.D.: "Operating experience with the Chino 10 MW/40 MWh battery energy storage facility", Proceedings of the 24th Intersociety Energy Conversion Engineering Conference, IECEC-89, vol. 3, pp. 1641-1645, 1989.

A two-year demonstration test program at the Chino 10 MW, 40 MWh battery energy storage facility, designed to demonstrate the costs, benefits and technical feasibility of the plant operating in a substation environment for energy management purposes, is described. Since startup, the Chino facility has undergone 46 cycles under various charge and discharge regimes. The primary purpose of the first series of tests was to establish baseline operating parameters for the facility for later comparison. These tests are discussed in some detail. The operation of the facility during these tests also afforded the opportunity to establish facility operating and maintenance procedures for this first-of-a-kind plant. Several capital improvements that were made to enhance the operation, monitoring and security of the plant are also described.

Rogers, J.D. et al.: "30-MJ SMES Energy Storage System for Electric Utility Transmission Stabilization", Proceedings IEEE, vol. 71, pp. 1009-1017, 1983.

Ross, R.: "Storage Battery and Charger Applications at FPL Company Transmission and Distribution Substations", Georgia Tech Protective Relaying Conference, April 30 - May 2, 1986.

Considerations in selecting and sizing the battery and charger are explained, with other considerations such as cable sizing and maintenance a detailed example of the entire process is included with actual drawings, specifications, and worksheets.

Roth, H.H.: "Electrical requirements of reversible pumped-storage units", AIEE Transactions, vol. 77, pp. 1129-1133, 1958.

Roth, H.H. & Armbruster, T.F.: "Starting Large Synchronous Machines", Paper 31PP66-548, ASME/AIEE Joint Power Generation Conference, Denver, September 18-22, 1966.

Roth, H.H. & Armbruster, T.F.: "Starting Large Pumping Units", Allis-Chalmers Engineering Review, vol. 31, no. 3, pp. 21-25, 1966.

Rufer A.C.: "Modern power conversion for complementary energy storage", Fifth International Conference on Power Electronics and Variable-Speed Drives, pp. 668-672, 1994.

Similar to the classical solution of hydraulic pump-turbine plants, new means for accumulation of electrical energy are given for lower but respectable quantities by the so called BESS (battery energy storage systems) and SMES (superconducting magnet energy storage). Another energy accumulator is given by using the mechanical kinetic energy of a flywheel. Each system has advantages and disadvantages from the point of view of the quantity of stored energy and magnitude of the instantaneous usable power. A realistic application of energy storage should combine different means of storage, using the advantages of their complementarity. Modern energy conversion techniques allow fast, and flexible power control, and also reactive power compensation.

Ruggeri, R.T.: "Advanced underwater power systems", Proceedings of the Sixth International Symposium on Unmanned Untethered Submersible Technol., pp. 153-167, 1989.

A long-endurance underwater power system has been under investigation at Boeing since 1985. The objective of this program is to develop a power system capable of providing at least 1000 kilowatt-hours of energy, and of operating continuously for more than 10 days. A number of systems are capable of meeting these requirements. The performance of power sources using artificial gills, cryogenic oxygen storage, chemical energy storage, and advanced batteries are compared. The relative merits of each system are discussed for different mission requirements. It is apparent from the data that no single type of power system can provide the requirements for power and energy of future UUVs (unmanned underwater vehicles). Most batteries and thermal cycle engines are far from meeting the desired goals, and it is unlikely that dramatically new systems or fundamentally different technology will be developed in the near future. Artificial gills could increase the energy density of UUV power systems by a factor of 5 over the lithium-thionyl chloride system and a factor of 8 over silver-zinc batteries. These systems also provide longer endurance.

Ruml, J. (Skoda Plzen): "Asynchronous starting of synchronous condensers and generator-motors in pumped storage plant", in Reichert, K. & Neubauer, R.E. (editors): Proceedings. International Conference on the Evolution and Modern Aspects of Synchronous Machines, Zurich, 27-29 August 1991, vol. 1, pp. 216-18, Institute of Electrical Machines, Zurich, 1991.

The author deals with the possibilities of eliminating the negative effects which occur during the starting of synchronous machines such as current rises, voltage drops in the high-voltage network, and mechanical stresses in the stator and damper windings. In motor-generator sets with low friction losses during starting, such as in the case of synchronous condensers or dewatered pump/turbine runners, the method of synchronous starting is shown to be of advantageous use. All calculations have been verified by measurements on motor-generators and synchronous condensers with solid poles.

Sakthivel, M. & Shanmugasundaram, S.: "Effect of energy storage medium (black granite gravel) on the performance of a solar still", International Journal of Energy Research, vol. 32, no. 1, pp. 68-82, 2008.

In this study, a detailed experiment has been conducted on a single-basin solar still which is modified with energy storage medium of black granite gravel. An attempt has been made to utilize the maximum amount of solar energy and to reduce the heat loss from the sides and bottom of the still. The conventional still is modified with an energy storage medium of black granite gravel of 6 mm size which is provided in the basin for different (quantity) depths. The black granite gravel functions as energy storage medium and also as an insulation layer to reduce the bottom and side loss coefficients. The black gravel is used for absorbing the excess heat energy from solar radiation during the noon hours. Due to this, the heat accumulated in the space between the water and glass surface is reduced and hence the temperature difference between the water and glass surfaces increases. The depth (quantity) of the gravel layer in the basin will influence the performance of the still and some of the parameters like basin temperature, water temperature, glass temperature and still productivity. This study deals with the effect of aforesaid parameters on the performance of the still. An attempt has been made to optimize the still performance for the above-mentioned parameters. A mathematical model is developed to estimate the water, gravel, and inside glass temperatures theoretically and to estimate the hourly and daily yield. To show the effectiveness of the modification, its performance is compared with the conventional still under the same climatic condi-

tion. It is found that the still yield is increased by 17-20% with almost no cost for this modification as black granite gravel is very cheap. Error analysis was done by comparing the theoretical and experimental results to show the validity of the mathematical model. It is found that the maximum percentage of discrepancy for all the parameters is about ±18%. Theoretical value of yield per day has 8% discrepancy over experimental value.

Salameh, Z.M.; Casacca, M.A. & Lynch, W.A.: "A Mathematical Model for Lead-Acid Batteries", IEEE Transactions on Energy Conversions, vol. 7, no. 1, pp. 93-97, March 1992.

Samolis, P.M.: "Electrical Features of the Northfield Pumped Storage Project", IEEE Transactions on Power Apparatus and Systems, vol. PAS-88, no. 8, pp. 1291-1297, August 1969.

Samolis, R.P.: "What's the Best Pump Start Mode for Big Pumps – Hydro?", Electric Light and Power, pp. 35-37, November 1970.

Sattler, P.K.: "Erwärmung der massiven Polschuhe von Synchronmotoren bei asynchronem Anlauf", ETZ-A, vol. 83, no. 24, pp. 807-810, 1962.

Saupe, R.: "The power conditioning system for the ±8,5/17 MW-energy storage plant of BEWAG", Third International Conference on Power Electronics and Variable-Speed Drives, pp. 218-220, 1988.

The electricity supply of West Berlin is operated by the Berliner Kraft- und Licht (BEWAG) and has been running as an insular system since 1952. In order to reduce the problems of this the utility company is considering using large-scale storage batteries in order to reduce cost for load frequency control and instantaneous reserve. The author looks at the design and some significant considerations when integrating a battery with an electric system.

Schaber, C.; Mazza, P. & Hammerschlag, R.: "Utility-Scale Storage of Renewable Energy", The Electricity Journal, vol. 17, no. 6, pp. 21-29, 2004.

For widespread renewable energy to become reality, it must be coupled with energy storage to match the intermittent renewable supply with customer demand. Hydrogen has been proposed as the energy storage medium of the future, but the utility industry might be better advised to consider such other methods as secondary batteries, flow batteries, compressed air, and pumped hydro.

Schimmoller, B.K: "Flexibility of emerging energy storage technologies offers commercial promise", Power Engineering, vol. 106, no. 11, pp. 112-118, 2002.

Much of the difficulty in designing good market rules can be traced to the fact that electricity cannot be readily stored. A number of energy storage technologies, however, are building commercial momentum, angling to cut in on the supply/load dance and facilitate market operation. The Energy Storage Council recently released a white paper outlining the case for energy storage. The white paper states that energy storage will create a far more responsive market by supplying power where and when needed. Only in the past few years have the power industry and the energy market evolved to the point where the benefits of storage are embraced as indispensable. Several storage techniques are discussed. Turning potential into reality remains a tall task, but the growing worldwide interest in energy storage, coupled with the numerous commercial and demonstration projects underway, indicates that the gap between potential and reality is shrinking.

Schmidhuber, P.M., Baumann, K.M.J. & Nowicki, P.: "Das Konstruktionskonzept der Pumpturbine für das Pumpspeicherwerk Leitzach", Elektrizitätswirtschaft, vol. 82, no. 24, pp. 889-894, 21 November, 1983.

Schweickardt, H.E.; Kobi, H. & Mitchel, A.S.: "12 MW / 6 000 rpm variable speed load commutated inverter drives for Matimba power station", Report 11-15, CIGRE Session, Paris, August - September 1986.

Sebastian, R.: "Smooth transition from wind only to wind diesel mode in an autonomous wind diesel system with a battery-based energy storage system", Renewable Energy, vol. 33, no. 3, pp. 454-466, 2008.

High wind penetration wind diesel hybrid systems (WDHS) have three modes of operation: Diesel Only (DO), Wind Diesel (WD) and Wind Only (WO). The WDHS presented in this article consists of a wind turbine generator (WTG), a diesel engine (DE), a synchronous machine (SM), the consumer load, a battery-based energy storage system (BESS), a discrete dump load (DL) and a distributed control system (DCS). The DE can be engaged (DO and WD modes)/disengaged (WO mode) from the SM by means of a clutch. The DCS consists of a sensor node, which measures the SM and DE speeds, calculates the reference active power PREF necessary to balance the active power in the WDHS and communicates this PREF value with a message to the BESS and DL actuator nodes. In the WO mode, the power sources are the WTG and the BESS (temporary) and if there is an active power shortfall, the DCS, to prevent a frequency collapse, must order to start the DE, wait until the DE reaches the SM speed and lock the clutch, changing to the WD mode. With the clutch locked, the combined actuation of the DE+BESS will raise the system frequency to the rated value. This WO to WD transition is simulated in this article showing graphs for frequency, voltage and active powers for the elements of the system. These graphs are compared with the ones obtained if the BESS does not actuate in WD mode. The comparison results show that with the BESS actuation in WD mode the settling time is reduced a 50%, the over and under shooting in the system frequency are eliminated and the system voltage variations are reduced a 40%.

Sellers, L.R. & Kirkland, J.E.: "Pumped-Turbine Unit 2 Addition at TVA Hiwassee Hydro Power Plant", AIEE Transactions (Power Apparatus and Systems), vol. 75, pp. 849-857, October 1956.

Sels T.; Dragu C.; Van Craenenbroeck T. & Belmans R.: "Overview of new energy storage systems for an improved power quality and load managing on distribution level", 16th International Conference and Exhibition on Electricity Distribution, 2001, Part 1: Contributions, IEE Conference Publication No. 482, vol.4, pp. 5, 2001.

Since a few years, problems regarding power quality issues in general become more and more of interest. Power quality problems have their own negative influence on both technical and economical aspects of modern society. Solving some of them as voltage sags, needs the input of large amounts of power (peak power during a short time). This input of energy requires of course different 'energy reservoirs'. Also to be sure that the supply and demand of electrical energy are in balance, it is sometimes recommended to own a 'bulk of energy'. During the years, several kinds of storage systems were developed for electrical energy and the research for new storage systems is still going on. Most systems store the electrical energy in an other type of energy. New systems are developed to store electrical energy in a direct way by using superconducting technologies and improved material characteristics. In this paper, the authors give a brief overview of those new technical solutions as superconducting magnetic energy storage, super capacitors and redox flow batteries. To make a comparison with other methods, (older or oncoming techniques), they are briefly discussed.

Selånger, P.& Ahlberg Tidblad, A.: "Litiumjonbatterier för stationära tillämpningar Del 1. Energibesparingsjämförelse vid ersättning av bly- och nickelkadmiumbatterier i reservkraftsystem", Catella Generics AB, Rapport från P12681-1, EFA-02/1, 2001.

Litiumjonbatteriet har vunnit stora framgångar under 1990-talet. Främsta anledningen till framgångarna är den betydande energitätheten, cirka 2-3 gånger högre, jämfört med nickel-kadmium och blybatterier. Li-jonbatteriet har främst vunnit mark i tillämpningar som mobiltelefoner och datorer och andra handburna applikationer. Den här rapporten söker besvara frågeställning om huruvida Li-jon-teknologin lämpar sig som ersättare till bly- och NiCd-batterier för stationära reservkraftstillämpningar ur energisparperspektiv. De faktorer som motiverar ersättning av framförallt blybatterier är behovet av en teknologi som har en livslängd och diagnosticerbarhet liknande den för andra kraftdistributionskomponenter. Andra önskemål är låga kostnader för underhåll samt att batterierna skall tåla högre arbetstemperaturer för att minska såväl energiförbrukningen för underhållsladdning som effektbehovet för kylning. Resultatet av energibesparingskalkylerna visar att Li-jonbatterier inte utgör ett alternativ för blybatterier som stationärt reservkraftsbatteri i sin nuvarande utformning. Li-jonbatterier kan däremot vara intressanta som ersättning för NiCd-batterier i mindre anläggningar.

Shepard S. & Van Der Linden, S.: "Compressed air energy storage adapts proven technology to address market opportunities", Power Engineering, vol. 105, no. 4, pp. 34-37, 2001.

The electric power industry is on the verge of a new era where many of the rules will be different, but the underlying requirements will be the same: reasonably priced power available on demand and produced in a cost-efficient and environmentally responsible manner. Compressed air energy storage (CAES) technology can play an important role in meeting market demand for electricity, addressing the need for intermediate and peaking power generation, where natural gas-fired turbines are most suitable. CAES technology uses low-cost, off-peak power to pressurize and store air that can later be expanded through a gas turbine during on-peak periods. While many industry participants are not very familiar with this technology, CAES power generation plants are based on proven technology for both compressed air storage and power generation.

Shiao, Y.S.; Lin, C.E.; Tsai, M.T. & Huang, C.L.: "Harmonic and reactive current compensation using a voltage source inverter in a battery energy storage system", Electric Power Systems Research, vol. 25, no. 1, pp. 25-33, 1992.

This paper presents a harmonic and reactive current compensator using a voltage source pulse-width modulated inverter. The proposed operation is included as part of the function of battery energy storage system in this study. The control strategy of inverter switching devices is based on the calculation algorithm from the instantaneous power theorem. Its main feature is to maintain the operation system with unit power factor, as well as to suppress the harmonic current generated from nonlinear loads. In this paper, different control methods are applied in simulations. Ramp control can be improved by a fine-tuned compensator, and its performance is proved both in simulation and experiment. In the battery energy storage system, the harmonic and reactive power control mode is also important to the overall operation. The proposed method promotes the battery energy storage system for wider applications.

Shireen, W. & Arefeen, M.S.: "An utility interactive power electronics interface for alternate/renewable energy systems", IEEE Transaction on Energy Conversion, vol. 11, no. 3, pp. 643-649, 1996.

The foreseeable shortages in conventional sources of electric power have increased the emphasis on the research and development of alternate sources of energy. In order to make a noteworthy impact the alternate sources of energy need to be utility interactive by means of a power electronic interface (a DC to AC converter). The inherent assumption in the control of DC to AC converters is that the DC voltage available at the input of the converter is constant. However, when the input is an unregulated DC source such as a battery, fuel cell, photovoltaic cells or any other form of alternate source, maintenance of the constant DC voltage at the input of the converter is often impossible. A modified inverter switching technique is proposed for the interface with the utility grid such that the AC output of the inverter becomes immune to fluctuations in the unregulated input DC obtained from alternate energy sources.

Xu, S.: "A self-starting two-speed synchronous generator-motor for pumped-storage power station. Concept (in Chinese)", Proceedings of the CSEE, vol. 14, no. 1, pp. 51-56, January 1994.

A self-starting pole-changing two-speed salient-pole synchronous generator-motor for pumped-storage power station applications is proposed in this paper. The mechanical structure of this new machine is quite similar to that of ordinary single-speed salient-pole synchronous machines, but the damping cage in the pole-shoe of the rotor is eliminated, and hence is much easier to manufacture. When the machine is used as a motor, any additional starting device is needless; the motor can be started directly online, with the merit of small starting current, large starting torque and easy synchronization. The new machines also have the advantages of: eliminating the danger of high voltage existence in the exciting windings; raising the dynamic stability of the machine; and improving the voltage waveform when the machine is used as a generator. Thus, use of this new machine-type in pumped-storage power stations can provide significant economic and social benefits.

Shoults, D.R.; Crary, S.B. & Lauder, A.H.: "Pull in Characteristics of Synchronous Motors", AIEE Transactions, vol. 54, pp. 1385-1395, 1935.

Shoyama, E.: "Synchronous Starting of Generator-Motor Units at Pumped Storage Power Stations", Hitachi Review, vol. 17, no. 1, pp. 2-7, 1968.

Shutt, C.C. & Dawson, J.W.: "Angle Switching of Synchronous Motors", AIEE Transactions, vol. 54, pp. 1385-1395, November 1935.

de Siervo, F. & Lugaresi, A.: "Modern trends in selecting and designing reversible Francis pump-turbines", Water Power & Dam Construction, vol. 32, no. 5, pp. 33-42, May 1980.

Simond, J.J.; Flach, E. & Balunga, W.: "Simultaneous frequency starting of large synchronous motor-generators in pumped storage plants", Proceedings. International Conference on Electrical Machines, Manchester, 15-17 September 1992, UK pp. 74-77, vol. 1, Manchester University, 1992.

A short description of the two main variants of the frequency starting of a single machine-back-to-back and partial frequency starting is first presented. Then, the extension to the simultaneous starting of two motor-generators is analysed. For a given configuration (machines, type of connection between the stators, break-away and retarding torques), the study leads to the optimal choice of the freely adjustable parameters (excitation levels, generator prime mover torque, as well as the initial generator speed in case of a partial frequency starting) in order to guarantee a successful start -up for any initial relative position of the rotors.

Simond, J.-J.; Vogele, H.; Chatelain, J. & Taghezout, D.: "Motor-generators in pumped storage plants-experiences, design features and starting modes", Proceedings of the International Symposium on Salient-Pole Machines with Particular Reference to Large-Size Hydro-Electric Generators and Large Synchronous Motors, Wuhan, 10-12 October 1993, pp. 360-371, Huazhong University of Science & Technology, Hubei, 1993.

Pumped -storage plants use electrical machines, which work in the motor mode as well as in the generator mode. A synchronous machine cannot start up without the help of a special starting assistance. In this paper, the authors report on experiences made with the following starting aids: pony motors, asynchronous starting, back-to-back, partial frequency and frequency converter starting. Experiences and design features of machines, which have been in operation for several years now, are discussed.

Singh, B.; Solanki, J.; Chandra, A.; Kamal-Al-Haddad: "A Solid State Compensator with Energy Storage for Isolated Diesel Generator Set", IEEE International Symposium on Industrial Electronics, vol. 3, pp. 1774-1778, 2006.

This paper presents the control of battery energy storage system (BESS) with diesel generator (DG) set. The performance of the DG set is observed best when operated at full load or near full load (up to 80-100% load) condition. For this purpose a BESS is employed which ensures the load on the generator remains in between 80% to 100% of full load. Under light load condition (load less than 80%) the battery is being charged and in heavy load condition (load more than 100%) energy from battery is utilized to feed extra power to the load and when load is in-between 80 to 100% battery remain in floating condition. Along with load management, BESS provides the reactive power, harmonic current and unbalanced load current compensation. The control of BESS is achieved using synchronous reference frame theory (SRF) to extract the balance positive sequence real fundamental frequency component of load current. The switching of voltage source converter (VSC) working as BESS is achieved by forcing source currents to follow reference currents using hysteresis based PWM controller. The complete system is simulated under MATLAB environment using SIMULINK and PSB block-sets to demonstrate the capabilities of the system.

Singh, B.; Solanki, J. & Chandra, A.: "Adaline based control of battery energy storage system for diesel generator set", IEEE Power India Conference, 2006.

This paper presents the operation of battery energy storage system (BESS) with diesel generator (DG) set. The performance of the DG set is observed best when operated at full load or near full load (up to 70-80% load) condition. For this purpose a BESS is employed which ensures the load on the generator remains in between 80% to 100% of full load. Under light load condition (load less than 80%) the battery is being charged and in heavy load condition (load more than 100%) energy from battery is also utilized to feed extra power to the load. Along with load management, BESS provides the reactive power, harmonic and unbalanced load current compensation. The control of BESS is achieved using least mean square (LMS) based Adaline. The Adaline is used to extract the balance positive sequence real fundamental frequency component of load current. The switching of voltage source converter (VSC) working as BESS is achieved by forcing source currents to follow reference currents using hysteresis based PWM control. The scheme is simulated under MATLAB environment using SIMULINK and PSB block-sets. The modeling is performed for 3-phase 4-wire star connected synchronous generator, along with the 4-leg VSC working as BESS. The results verify the effectiveness of the Adaline based control of BESS to meet load compensation and optimal operation of DG set.

Singh, B.; Kasal, G.; Chandra, A. & Kamal-Al-Haddad: "Battery Based Voltage and Frequency Controller for Parallel Operated Isolated Asynchronous Generators", IEEE International Symposium on Industrial Electronics, pp. 883-888, 2007.

This paper deals with a battery energy storage system (BESS) based voltage and frequency (VF) controller for parallel operated isolated asynchronous generators (IAGs) driven by uncontrolled pico hydro turbines used in constant power applications. The individual AC capacitor banks are used to generate the rated voltage at no load while additional demand of reactive power for the load and generators is met by the controller. The proposed is having capability of harmonic elimination, load balancing and load leveling along with voltage and frequency control. The proposed controller is realized using an IGBT (Insulated Gate Bipolar Transistor) based voltage source converter (VSC) and battery system at its DC link. Since the VSC allows bidirectional flow of active and reactive power; thus it regulates the voltage and frequency. The effectiveness of the proposed controller is demonstrated through the MATLAB based simulations using Simulink and PSB (Power System Block set) toolboxes and different aspects of the controller are studied for parallel operated isolated asynchronous generators.

Skjellnes, A.: "A UPS with Inverter Specially Designed for Nonlinear Loads," IEEE/ INTELEC Conference Records, 1987.

Smith, A.M.: "Reliability-Centered Maintenance", McGraw-Hill, New York, 1993.

Sono, M.; Fukumasu, K.; Watanabe, T. & Mutaguchi, K.: "Design and Manufacture of Francis Type Reversible Pump Turbines", Mitsubishi Technical Review, February 1977.

Spindler, W.C.: "Lead/acid batteries in utility energy storage and power control applications", Journal of Power Sources, vol. 35, no. 4, pp. 395-398, 1991.

Several types of benefits can be obtained with installations of lead/acid batteries at strategic locations in service areas of electric power utility companies, and also at large customer sites. Examples will be given of representative projects in different countries, some operational, and some to be built. Increasing use of lead/acid battery energy and power storage systems could be favored by improving the performance characteristics of sealed, recombination designs.

Stasevich, S.G.: "Calculating the voltage levels in the DC networks when a differential busbar protection operates outdoor switchgear", (in Russian), Elektricheskie Stantsii, no. 12, pp. 54-56, 1983.

The author studies some design features of the DC operating supply for a differential protection (battery, charger, switching, voltage regulator, back-up system and distribution network) and the problems of calculating the voltage levels when the protection operates. A main difficulty is the nature of the variation in current through the trip coils of the air-blast circuit breakers. A method is proposed for calculating the voltage on the trip coils when the busbar protection operates, taking into account the non-linearity of the internal resistances of battery and trip coils. An algorithm enables the ability of a specific battery to provide the necessary voltage on the relay protection and automatic-control circuits when several circuit breakers are being tripped at once, to be calculated. The permissible voltage drops in the distribution networks can also be calculated.

Stein, H.: "Utilities use some energy storage concepts, but find others hard to implement", Electric Light & Power, vol. 71, no. 12, pp. 24-27, 1993.

Focuses on energy storage technology used by electric utilities in the United States. Advantages of energy storage; Pumped storage technology; Compressed-air energy storage (CAES); Battery-energy storage system (BESS); Superconducting magnetic energy storage (SMES) devices; Thermal energy storage.

Sugimoto, O.; Haraguchi, E.; Kuwabara, T.; Hitomi, I.; Bando, A. & Nagura, O.: "Developments Targeting 400 MW Class Adjustable Speed Pumped Hydro Plant and Commissioning of 18.5 MW Adjustable Speed Hydro Plant", ASME Fifth International Symposium on Hydro Power, Fluid Machinery – FED, vol. 68, pp. 71-79, November 1988.

Swider, D. J.: "Compressed Air Energy Storage in an Electricity System with Significant Wind Power Generation", IEEE Transactions on Energy Conversion, vol. 22, no. 1, pp. 95-102, 2007.

In this paper, a stochastic electricity market model is applied to estimate the effects of significant wind power generation on system operation and on economic value of investments in compressed air energy storage (CAES). The model's principle is cost minimization by determining the system costs mainly as a function of available generation and transmission capacities, primary energy prices, plant characteristics, and electricity demand. To obtain appropriate estimates, notably reduced efficiencies at part load, start-up costs, and reserve power requirements are taken into account. The latter are endogenously modeled by applying a probabilistic method. The intermittency of wind is covered by a stochastic recombining tree and the system is considered to adapt on increasing wind integration over time by endogenous modeling of investments in selected thermal power plants and CAES. Results for a German case study indicate that CAES can be economic in the case of large-scale wind power deployment

Takase, M.;Okada, M.; Takagi, N.;Tateishi, S. & Tamatsukuri, T.: "Recent Large Capacity Pump-turbines and Generator-motors", Hitachi Review, vol. 20, no. 7, pp. 294-301, July, 1971.

Takase, M. et al.: "310 000 kW Francis Type Pump Turbine for Okutataragi Power Station, Kansai Electric Power Co.", Hitachi Review, vol. 23, no. 9, pp. 337-, 1974.

Takase, M. et al.: "Field Test Results of 310 000 kW Pump Turbines for Okutataragi Power Station, Kansai Electric Power Co.", Hitachi Review, vol. 24, no. 7, pp. 285-, 1975.

Takoh, T. & Yamamoto, K.: "The rapid progress of pump-turbine design and techniques", Water Power, no. 2, pp. 71-77, February, 1972.

Talalov, I.I.; Mishukov, V.K.; Gorshkov, A.P. & Shelikalov, U.J.: "An accurate calculation for the frequency and starting characteristics of salient pole synchronous machines", Elektrichestvo, no. 4, pp. 47-53, 1970.

Tamura, ? et al.: "Analysis of AC excited synchronous machine – Transient condition", Journal of the Institute of Electrical Engineers of Japan, vol. 104-B, p. 17, 1984.

Tanaka, H., Ito, S. & Fujisaki, M.: "Kisen'yama Pumped-Storage Power Station. Part 1. 240-MW (322,000-HP) Reversible Pump-Turbine", Toshiba Review, pp. 5-11, February 1971.

Tari, M.H. & Soderstrom M.: "Optimization modelling of industrial energy systems using MIND introducing the effect of material storage", European Journal of Operational Research, vol. 142, no. 2, pp. 419-433, 2002.

> Strategic decisions regarding industrial energy systems should ideally involve the entire plant. Systems analysis using optimization methods identifies the minimum cost solution among numerous alternatives. In the deregulated Swedish energy market, there are large variations in electricity contracts. These contracts affect the possibilities of industrial energy systems to react not only through the price level but also through the price structure. Material storage can affect an industrial system in many ways. One of them is that material storage can prevent a situation in which different parts of an industrial system with different production rates counteract each other. In this paper, the influence on energy costs of the use of material storage is discussed. The importance of modeling material storage has been shown, especially in situations where there are time-of-use-prices of electricity. A case study from the pulp and paper industry has been used to confirm this.

Tari, M.H.; Söderström, M.: "Optimisation modelling of industrial energy systems using MIND introducing the effect of material storage", European Journal of Operational Research, vol. 142, no. 2, pp. 419-433, 2002.

> Strategic decisions regarding industrial energy systems should ideally involve the entire plant. Systems analysis using optimisation methods identifies the minimum cost solution among numerous alternatives. In the deregulated Swedish (and European) energy market, there are large variations in electricity contracts. These contracts affect the possibilities of industrial energy systems to react not only through the price level but also through the price structure. Material storage can affect an industrial system in many ways. One of them is that material storage can prevent a situation in which different parts of an industrial system with different production rates counteract each other. In this paper, the influence on energy costs of the use of material storage is discussed. The importance of modelling material storage has been shown, especially in situations where there are time-of-use-prices of electricity. A case study from the pulp and paper industry has been used to confirm this.

Tari, M.H. & Söderström, M.: "Modelling of thermal energy storage in industrial energy systems the method development of MIND", Applied Thermal Engineering, vol. 22, no. 11, pp. 1195-1205, 2002.

> Industrial energy efficiency is of vital importance as regards environment and industrial profitability. Optimisation of industrial energy systems may show a way towards improved use of resources in energy supply as well as in production processes. The deregulation of the electricity market in some countries increases flexibility in electricity contracts. Taking advantage of the price structure in these contracts is one of the ways to minimise the energy costs and decrease the influence on the environment. Thermal energy stores are very suitable facilities for achieving these goals, having the capability of moving energy use from one period of time to another and thereby influencing not only energy cost but also costs related to power demand if electric energy use is involved.In this paper, the influence on energy costs, energy and material flows resulting from the use of energy storage is discussed. Energy storage has been modelled by using MIND (Method for analysis of INDustrial energy systems) in the form that has recently been developed by the author. A case study from the pulp and paper industry has been used to verify this.

Taylor, P.: "Spinning reserve in Puerto Rico doesn't spin - It's a battery", Electrical World, vol. 209, no. 4, pp. 42-45, 1995.

Puerto Rico Electric Power Authority's (PREPA) new battery energy-storage facility in San Juan provides the island with 20 MW and 14.1 MWh for frequency control and instantaneous spinning reserve. A self-commutated power-conditioning system (PCS) also enables black starts and provides reactive power for voltage control on transmission lines. PREPA built this multiple-function facility because a battery energy storage system could more cost-effectively provide power and energy than any other storage technology or generating option. Engineers analyzed a variety of options to achieve the 300 MW of spinning reserve that the system needed, including load management, upgrading existing generating facilities and installing energy-storage technologies. The PCS consists of two 10-MVA, voltage-sourced, self-commutated, gate-turnoff thyristor converters. The control system initiates battery discharge through distributed controllers when the electrical frequency drops from 60.0 to 59.2 Hz.

Teissier, D. & Pouliquen, J.-L. (Div. de Ensembles Ind., Cegelec, Belfort): "SFCs for starting large synchronous machines at pumped- storage plants", International Journal on Hydropower & Dams, vol. 4, no. 5, pp. 86-90, 1997.

Static frequency converters used for starting synchronous machines have the advantages of operating flexibility and the ability to help improve the reliability of installations. This paper describes how recent technical progress has led to extensive simplification of such power converters and their associated control systems.

Tengstrand, C.: "Start av motorerna in pumpstationen Dos Amigos", ASEA Tidning, pp. 28-29, 1969.

Thomas, K.: "TVA energy storage project decision expected in 'weeks'", Electric Light & Power, vol. 78, no. 12, pp. 27-27, 2000.

Reports on the partnership between the Tennessee Valley Authority and British company Innogy Holdings PLC to develop an electricity storage system. Construction cost of the system; Features of the system; Advantages that will be provided by the system to both companies.

Thote, F.: "20 Jahre in Betrieb: Pumpspeicherwerk Vianden", Elektrizitätswirtschaft, vol. 83, no. 24, pp. 1019-1024, 19 November, 1984.

Thottuvelil, V.J.; Kakalec, R.J. & Valenta, J.F.: "Causes and control of common-mode transients induced by fuse-blowing in battery plants", Twentieth International Telecommunications Energy Conference, 1998, INTELEC, pp. 137-142, 1999..

Common-mode transients can be induced when protection devices such as fuses or circuit breakers blow due to faults that occur between the feeder and ground. Such transient voltages can be substantially larger than the powering voltage and could lead to breakdown of equipment. The mechanisms that cause these transients and a method for limiting the transients to safe levels are described using experimental measurements from an actual plant and simulation models. The impact of different fuse characteristics on the transients is also discussed.

Ming-Tsung Tsai; Chin-E Lin; Wen-Inne Tsai & Ching-Lien Huang: "Design and implementation of a demand-side multifunction battery energy storage system", IEEE Transactions on Industrial Electronics, vol. 42, no. 6, pp. 642-652, 1995.

This paper presents a new control strategy in a battery energy storage system (BESS) for multifunction operation. The multifunction BESS operates in two modes: one is the parallel processing mode which can play as an active filter, a power conditioner, or a voltage stabilizer; and the other is the stand-alone mode which acts as a conventional uninterruptible power supply. Basic principle from the conventional control method is used and modified to accomplish the desired operation function. The proposed theoretical formulations are verified by system analysis and simulation to present its performance. A laboratory prototype is fabricated and tested to support the proposed idea of a multifunction battery energy storage system.

Tsang, M.W. & Sutanto, D.: "Damping inter-area oscillation using a battery energy storage system", Fourth International Conference on Advances in Power System Control, Operation and Management, APSCOM-97, Conf. Publ. No. 450, vol. 2, pp. 409-414, 1997.

The paper describes some control strategies developed for battery energy storage systems (BESS) to damp inter-area oscillation, a growing problem to many utilities in the world, as more and more are dependent on interconnections. This paper describes the use of several control strategies of using different damping signals and controllers such as PI controllers and novel artificial intelligence control techniques such as fuzzy logic control to modulate the active and reactive power outputs of the BESS. Preliminary studies show that both types of controllers can provide significant damping. This paper also discusses how to determine the best location for placing BESS to damp inter-area oscillation, particularly when different control strategies are used.

Tsang, M.W. & Sutanto, D.: "Control strategies to damp inter-area oscillations using a battery energy storage system", Proceedings of the IEEE International Conference on Energy Management and Power Delivery, EMPD '98, vol. 1, pp. 241-246, 1998.

The paper describes our investigation of several control strategies for use with a battery energy storage system (BESS) to damp inter-area oscillation, such as PI controllers and novel artificial intelligence control techniques utilising a fuzzy logic controller to modulate the active and reactive power output of the BESS. Preliminary studies show that both types of controllers can provide significant damping. Fuzzy logic controllers can provide superior performance in its ability to damp machine oscillation. The use of bus voltage signals to control the reactive power output of the BESS is found to provide very little damping.

Tsang, M.W. & Sutanto, D.: "Power system stability improvement using energy storage with fuzzy logic controller", International Conference on Advances in Power System Control, Operation and Management, APSCOM-00, vol. 2, pp. 322-326, IEE, 2000.

A fuzzy logic controller (FLC) is designed for a battery energy storage system (BESS) to improve the stability of an interconnected multi-machine power system. The studied system consists of two generating areas interconnected by a long transmission line. A detailed model of BESS is developed for accurate dynamic assessment. The model takes into account the switching actions of the converter as well as the battery characteristics. This paper also describes the use of hysteresis technique to control directly the BESS output current. This reduces the complexity of the control system while at the same time provides a tight control of the BESS output. Test results under a variety of disturbances show the proposed BESS is effective in damping out power system oscillations.

Tsang, M.W. & Sutanto, D.: "Power system stabiliser using energy storage", IEEE Power Engineering Society Winter Meeting, vol. 2, pp. 1354-1359, 2000.

A fuzzy logic controller (FLC) and an artificial neural network (ANN) controller are designed for a battery energy storage system (BESS) to improve the stability of power systems. Both single-machine-to-infinite-bus and interconnected multi-machine power systems are considered in this study. A detailed model of BESS is used for accurate dynamic assessment. The model takes into account the switching actions of the converter as well as the battery characteristics. Another novel aspect of this paper is the use of hysteresis technique to control directly the BESS output current. This reduces the complexity of the control system while at the same time provides a tight control of the BESS output. Test results under different disturbances and operating conditions show the proposed BESS is effective in damping out power system oscillations.

Utrecht, M.: "Reduzierung thermischer Kräfte in Lagerstützkonstruktionen bei vertikalen Wasserkraftgeneratoren", Siemens Energetechnik, no. 5, 1982.

Vajda, I.; Kohari, Z.; Benko, L.; Meerovich, V. & Gawalek, W.: "Investigation of joint operation of a superconducting kinetic energy storage (flywheel) and solar cells", IEEE Transactions on Applied Superconductivity, vol. 13, no. 2, part-2, pp. 2169-2172, 2003.

Superconductors provide unique possibilities for storage of electricity, which is especially important for the reliability of networks supplied by renewable energy sources such as solar energy and wind energy. A system consisting of an HTS-based levitated flywheel as the energy storage unit and solar cells as the power supply was installed and investigated as a model of a viable variant of the mini-power plant concept. Measurements were performed to obtain information about relevant storage characteristics such as efficiency and stability. Possibilities of fitting the storage unit to the solar supply were also investigated in order to get maximum charge and discharge efficiency.

Vetter, K.J.: "Electrochemical Kinetics", Academic Press, New York, London, 1967.

Viedenz, U.: "Die Krafthausbaugrube der Pumpspecherwerks Leitzach I (neu) der Stadtwerke Elektrizitätswerke München", Die Bautechnik 7 and 8, 1984.

Vinal, G.W.: "Storage Batteries", John Wiley & Sons, New York, 1955.

Voelker, E.T. & Wilderson, C.R.: "Report on National Science Foundation Study Tour for Pumped-Storage Technology", Paper C 75 233-2 presented at the IEEE/PES Winter Meeting, January 26-31, 1975

Wada, et al.: "Analysis of Flow in Pump Turbine Runner FLANPT and Its Application", Hitachi Review, vol. 22, no. 10, October 1973.

Waldron, R.D.: "Unconventional systems for lunar base power generation and storage", Proceedings of the Intersociety Energy Conversion Engineering Conference, vol. 1, pp. 434-439, 1990.

The extended duration of the lunar night and the high specific mass of Earth-imported energy storage systems (regenerative fuel cells, batteries, etc.) render PV (photovoltaic) and import storage power systems non-competitive with nuclear power plants for lunar bases. However, power storage or generation methods, which can be constructed, using primarily lunar materials, used either alone or with lightweight PVs, can be attractive alternatives to nuclear power. Three generic systems which can provide favourable low-import-mass goals have been identified and studied: 1) gravitational energy generation using lunar soil; 2) thermal energy storage using basalt rock or glass; and 3) electrochemical storage using lunar-derived electrodes or fuels. The design, structural, and operational features of these methods are described.

Walker, J.H.: "Generator/motor problems in pumped-storage installations", The Proceedings of the Institution of Electrical Engineers, vol. 107, pt. A, pp. 157-165, 1960.

Walker, J.H.: "Hydro-electric machines for pumped storage", AEI Journal, vol. 1, pp. 51-61, 1961.

Walker, L.H.: "10 MW GTO converter for battery peaking service", Conference Record of the 1988 IEEE Industry Applications Society Annual Meeting, pp. 850-858, 1988.

The description is given of a bidirectional 18-pulse voltage source converter utilizing gate turn-off thyristors (GTOs). The converter, which is rated at 10 MVA, has been placed in service to connect an energy storage battery to a utility grid. The converter is rated and controlled to operate in all four quadrants (discharge, charge, leading VArs, or lagging VArs) at the full 10 MVA rating. It is capable of independent, rapid control of real and reactive power with a transient response of 16 ms to changes in commanded value of real or reactive power. Thus it is usable as a reactive power controller (static VAr control), voltage control, frequency control, power system stabilizer, or as a real power peaking station. The author describes the design, construction, control, and application of the converter, and gives performance data taken at the installation.

Walker, L.H.: "10-MW GTO converter for battery peaking service", IEEE Transactions on Industry Applications, vol. 26, no. 1, part-1, pp. 63-72, January 1990.

A bidirectional 18-pulse voltage-source converter utilizing gate-turnoff thyristors (GTOs) is described. The converter, which is rated 10 MVA, was placed in service in early 1988 to connect an energy storage battery to a utility grid. The converter is rated and controlled to operate in all four quadrants (discharge, charge, leading VAr, or lagging VAr) at the full 10 MVA rating. It is capable of independent rapid control of real and reactive power with a transient response of 16 ms to changes in commanded value of real or reactive power. Thus it is usable as a reactive power controller (static VAr control), voltage control, frequency control, power system stabilizer, or real power peaking station. For use as a reactive power controller only, no battery would be needed. The design, construction, control, and application of the converter are described, and performance data taken at factory power test and at the installation are given.

Weber, O.: "The air-storage gas turbine power station at Huntorf", Brown Boveri Review, vol. 62, no. 7/8, pp. 332-337, July 1975.

Wehenkel, L.: "Endausbau des Pumpspeicherwerkes Vianden", Elektrizitätswirtschaft, pp. 347-356, 1970.

Weinmann, O.: "Hydrogen - the flexible storage for electrical energy", Power Engineering Journal, vol. 13, no. 3, pp. 164-170, 1999.

The quality of life in society is directly linked to the access to energy. To achieve a high standard of living, the energy supply must be safe, reliable and affordable for everybody. Moreover, the energy supplied to customers should be usable for various applications. This suggests electrical energy which can be easily transformed to all the needs of the customer: power; heat; light; and communication. Therefore the trend to increase the utilisation of electricity in customer applications will continue in the future. Electrical energy, however suffers from some disadvantages: transportation is only possible over limited distances and needs a network; also direct storage systems for large capacity systems are mainly in the prototype and demonstration phases of development. The introduction of hydrogen will help to overcome these difficulties as it can be easily produced by electrical energy via electrolysis and reconverted to electricity by power plants. This article describes various activities being carried out by certain German utilities in conjunction with other European and Canadian utilities in preparing the way for the introduction of integrated hydrogen energy carrier systems within traditional fuel based energy infrastructures.

Wikström, P.; Terens, L.A. & Kobi, H.: "Reliability, Availability, and Maintainability of High-Power Variable-Speed Drive Systems", IEEE Transactions on Industry Applications, vol. 36, no. 1, pp. 231-241, January/February 2000.

Wolf, E.: "880-MW-Pumpspeicherwerk Waldeck II in Bau", Siemens-Zeitschrift, vol. 45, pp. 151-154, 1971.

Wolff, N. et al.: "The 140 MW Rönkhausen Station in West-Germany", Water Power, pp. 81-88, 1970.

Wright, L.S. & Brinson, E.M.: " The Design, Application, and Testing of Electrical Power Systems at the Bad Creek Pumped Storage Project", IEEE Transactions on Energy Conversion, vol. 7, no. 1, pp. 15-19, January 1992.

Xu, W.; Mansour, Y.; Siggers, C. & Hughes, M.B: "Developing utility harmonic regulations bases on IEEE Std 519 – B. C. Hydro's approach", IEEE Transactions on Power Delivery, vol. 10, pp. 1423-1431, 1995.

Yamamoto, H.; Hiraki, E.; Konishi, Y.; Nishida, K.; Horiuchi, T.; Sugawara, Y. & Nakaoka, M.: "Utility-interactive three-phase soft-switching pulse width modulated converter with active resonant snubbers in bridge leg sides for energy storage devices", Proceedings of the 25th Annual Conference of the IEEE Industrial Electronics Society, vol. 2, pp. 897-902, 1999.

In this paper, a prototype of a multi-functional controlled three-phase voltage-source bidirectional zero voltage soft-switching PWM converter with three auxiliary active resonant commutated snubber link (ARCS) is presented for battery and/or electric double layer capacitor energy storage system (BESS). The operating principle of this active resonant snubber-assisted soft-switching converter circuit for BESS and multi-functional digital control-based converter system including active rectifier and inverter operation modes are described. Operation characteristics of this bidirectional three phase soft-switching space voltage vector modulated converter with ARCS for BESS is demonstrated under the conditions of battery discharging-based peak-cut mode and battery charging-based energy storage mode in with conventional utility three phase hard-switching converter for BESS. The effectiveness of the converter system is proved on the basis of simulation analysis.

Yamamoto, H.; Inaba, C.Y.; Hiraki, E. & Nakaoka, M.: "Multifunctional digitally-controlled bidirectional three-phase soft-switching PWM converter", Eighth International Conference on Power Electronics and Variable Speed Drives, IEE Conf. Publ. No. 475, pp. 86-90, IEE, London, 2000.

In this paper, a prototype of a multifunctional controlled three-phase voltage-source bidirectional zero voltage soft-switching PWM converter with three auxiliary active resonant commutated snubber link (ARCSL) is presented for battery and/or electric double layer capacitor energy storage system (BESS) and active power filter system (APFS). The operating principle of this active resonant snubber-assisted soft-switching converter circuit and multi-functional digital control-based converter system including active rectifier and inverter operation modes are described. The effectiveness of a soft-switching bidirectional converter system is proved on the basis of simulation analysis.

Yamamoto, K.; Nishinoiri, K.; Kitano, Y.; Nagata, I. & Minato, A.: "240 000 kW Pump-turbine and Generator-motor for Kisenyama Pumped Power Station", Hitachi Review, vol.20, no. 7, pp. 276-285, July 1971.

Yamato, I.; Tokunaga, N.; Matsuda, Y.; Amano, H. & Suzuki, Y.: "New conversion system for UPS using high frequency link", Power Electronics Specialists Conference, PESC '88, vol. 2, pp. 658-663, 1988.

A novel conversion system for a UPS (uninterruptible power supply) using a high-frequency link is described. The UPS consists of a high-frequency inverter and transformer and a cycloconverter. The cycloconverter can be operated by both source commutation and self-commutation (by turning off the switching devices). A choice is made between the two commutation methods, depending on switching device losses during commutation and the internal voltage drop caused by commutating reactance. A compact and efficient UPS can be realized with this conversion system.

Yanagisawa, T.; Kageyama, T.; Okamura, K.; Kusonoki, K.; Taguchi, T.; Abe, M. & Kaneko, H.: "Transient Analysis of Converter-fed Adjustable Speed Generator-motor for the pumped Storage Power Plant", Journal of the Institute of Electrical Engineers of Japan, vol. 115-B, no. 2, p. 117, 1995.

Yanagisawa, T.; Kageyama, T.; Okamura, K.; Kusonoki, K.; Taguchi, T.; Abe, M. & Kaneko, H.: "Transient Analysis of Converter-fed Adjustable Speed Generator-motor for the pumped Storage Power Plant", Electrical Engineering in Japan, vol. 116, no. 2, pp. 63-76, 1996.

Yang, Z.; Shen, C.; Zhang, L.; Crow, M.L. & Atcitty, S.: "Integration of a StatCom and battery energy storage", IEEE Power Engineering Society Summer Meeting, vol. 3, pp. 1798, 2001.

The integration of an energy storage system, such as battery energy storage (BESS), into a FACTS device can provide dynamic decentralized active power capabilities and much needed flexibility for mitigating transmission level power flow problems. This paper introduces an integrated StatCom/BESS for the improvement of dynamic and transient stability and transmission capability; compare the performance of the different FACTS/BESS combinations, and provide experimental verification of the proposed controls on a scaled StatCom/BESS system.

Yang Z.; Shen C.; Zhang L.; Crow M.L. & Atcitty S.: "Integration of a StatCom and battery energy storage", IEEE Transactions on Power Systems, vol. 16, no. 2, pp. 254-260, 2001.

The integration of an energy storage system, such as battery energy storage (BESS), into a FACTS device can provide dynamic decentralized active power capabilities and much needed flexibility for mitigating transmission level power flow problems. This paper introduces an integrated StatCom/BESS for the improvement of dynamic and transient stability and transmission capability; compares the performance of the different FACTS/BESS combinations, and provides experimental verification of the proposed controls on a scaled StatCom/BESS system.

Yao, M.: "Fuel Cells: Their Application, Technological Status, Market and Opportunity", NEMO-report 4, Helsinki University of Technology, Helsinki, 1988, ISBN 951-754-679-3.

Yau, T.; Walker, L.N.; Graham, H.L.; Gupta, A. & Raithel, R.: "Effects of Battery Storage Devices on Power System Dispatch", IEEE Transactions on Power Apparatus and Systems, vol. PAS-100, no. 1, pp. 375-383, 1981.

Electric utilities are employing large fossil and nuclear generating plants which are difficult to cycle to follow load. Additionally, it is very expensive to provide regulation with large fossil plants and government regulations prohibit the use of nuclear plants for regulation. The inability to cycle large plants produces a need for energy storage devices. Currently, several projects are underway to develop batteries to provide energy storage for peak shaving and load leveling. The batteries have a fast rate of response and therefore can potentially be used to provide regulation, thus improving the area control error (ACE).

Luo Yingli; Wang Yanping; Li Hongguo; Huang Shipeng: "Study of the variable frequency start-up process of pumped storage machines. I. The mathematical model of variable frequency starting process of pumped storage machines", Proceedings of the International Symposium on Salient-Pole Machines with Particular Reference to Large-Size Hydro-Electric Generators and Large Synchronous Motors, Wuhan, 10-12 October 1993, pp. 153-159, Huazhong University of Science & Technology, Hubei, 1993.

In this paper both forced commutation range and natural commutation range are studied by means of the method of numerical solution of the state equation. The equation is obtained according to the two-axis theory of synchronous machines. The characteristics describing the starting process are given. The advantage of the model and calculation method of this paper lies in that it can give a more accurate account of the influence of alternating components of exciting current and damper windings on the starting process.

Luo Yingli; Wang Yanping; Li Hongguo & Huang Shipeng: "Study of the variable frequency start-up process of pumped storage machines. II. Some factors acting on start-up process of pumped storage machines", Proceedings of the International Symposium on Salient-Pole Machines with Particular Reference to Large-Size Hydro-Electric Generators and Large Synchronous Motors, Wuhan, 10-12 October 1993, pp. 160-164, Huazhong University of Science & Technology, Hubei, 1993.

The influence of initial frequency and closed angle of current in the forced commutation range on starting and the influence of overlap angle and advance angle in the natural commutation range on starting are studied by a numerical simulation method with consideration of AC component of exciting current and d and q axes damping currents.

Zaugg, P.: "Energiespeicherung mit Erdgas und Luft", Bull. SEV, vol. 77, no. 9, pp. 505-511, 10 May, 1986.

Zhan Changjiang; Wong Manchung; Han Yu; Han Yingduo & Zhao Liangbing: "Universal custom power conditioner (UCPC) in distribution networks", Proceedings of the IEEE International Conference on Power Electronics and Drive Systems, vol. 2, pp. 1067-1072, 1999.

> In this paper, a general powerful circuit of a universal custom power conditioner (UCPC), which is used to improve power reliability and quality applied to distribution networks, is presented in detail. The UCPC is based on series and shunt tri-level PWM converters with a battery energy storage system (BESS) for multi-function operations such as harmonic elimination, reactive power control, voltage sags compensation and uninterruptible power supply (UPS). The basic algorithm of system is deadbeat control with a repetitive compensation strategy based on the voltage space vector PWM method. Some simulation results are use to verify that UCPC can synthetically fulfill different compensation functions.

Changjiang Zhan; Munchung Wong; Zhiyong Wang & Yingduo Han: "DSP control of power conditioner for improving power quality", IEEE Power Engineering Society Winter Meeting, vol. 4, pp. 2556-2561, 2000.

> Based on the concept of customer power, the paper proposed a new device that is universal custom power conditioner (UCPC). The UCPC has series and shunt power converters with a battery energy storage system (BESS) for multi-function operation to compensate the voltage variation, flicker, reactive power, harmonics, imbalance, uninterruptible power supply, peak load power supply, active and reactive power control in transmission systems. The circuit and control topologies are addressed. A control structure based on dual DSP TMS320C32 and synchronous A/D sampling technology are discussed.

Zhang, I.; Crow, M.L.; Yang, Z. & Chen, S.: "The steady state characteristics of an SSSC integrated with energy storage", IEEE Power Engineering Society Winter Meeting, vol. 3, pp. 1311-1316, 2001.

> A static synchronous series compensator (SSSC) integrated with an energy storage system (ESS) can provide superior performance in power flow control, transient stability improvement and power oscillation damping. This paper focuses on comparing the steady state characteristics of the SSSC with ESS and without ESS. The SSSC output voltage range, compensated output power, operating modes and its effects on transmission line power flow control are extensively discussed using characteristic curves. Based on these curves, a new generalized PQ decoupled control concept is proposed for an SSSC with a battery energy storage system (BESS). The experimental validation of the proposed control is carried out on a laboratory SSSC/BESS setup.

Zeng, J.; Zhang, B.; Mao, C. & Wang, Y.: "Use of Battery Energy Storage System to Improve the Power Quality and Stability of Wind Farms", IEEE International Conference on Power System Technology, pp. 1-6, 2006.

> This paper presents the use of battery energy storage system for power smoothing in generation systems in which power flow variations can occur. These variations are the norm in wind energy generation. A simulation model for a battery energy storage system and a wind farm using squirrel cage induction generators magnetized with fixed capacitor banks are presented. And a decoupling and feed forward compensating control strategy is proposed. Simulations have been carried out and demonstrate that the BESS has the potential to significantly improve the wind farm's performance. Through control of the charging and discharging of the BESS using a power electronic interface, it is shown that the wind farm's output power can be controlled to a constant value. In addition, there is an overall improvement in the transient and dynamic response of the system.

Zmood, R.B.; McCluskey, T.A.; Rand, D.A.J. & Baldsing, W.G.A.: "Domestic remote-area power supplies: modeling battery usage for energy storage", Proceedings of the 24th Intersociety Energy Conversion Engineering Conference, IECEC-89, pp. 1689-1694, 1989.

The authors report on the development of methods for simulating the typical operating duty cycle of lead/acid batteries in remote area power supply (RAPS) systems. In developing test cycles for batteries, a RAPS computer simulation program called SOLSIM was used. The structure of SOLSIM and the effect on overall RAPS performance of the variation in key system and control algorithm parameters is discussed. The approach results in the derivation and application of battery load-current profiles for assessing the performance of both prototype and commercial lead/acid batteries.

"Back-to-Back Starting of Pump-Turbine Sets", Water Power, pp. 332-333, August 1968.

"Batteries-Power When You Need It", Power Sources and Supplies Conference Proceedings, ERA-87-0068, ISBN-0-7008-0363-7, London, 28 April 1987.

The International Conference on Power Sources and Supplies held during the 1987 British Electronics Week at Olympia covered three main technical areas: power supplies, batteries and solar photovoltaics. The theme of the conference was the application and exploitation of these three sources of power in electronic systems. The report, Part 2 of the conference proceedings, covers batteries. The papers presented cover batteries for UPS applications, distributed battery systems, batteries for PCB mounting, electric vehicle power systems, state of charge monitoring solid state batteries, effective management of nickel cadmium batteries, batteries in portable products, solid state fuel cells, batteries for photovoltaic systems. The proceedings include these papers, those from the UPS session included in Part 2, and the contributions made by delegates in the discussion periods. A delegate list and list of exhibitors at the Power Sources and Supplies Exhibition are also included.

"Bibliography on pumped storage to 1975", Hydroelectric Power Subcommittee of the IEEE Power Generation Committee, IEEE Trans. on Power Apparatus and Systems, vol. PAS-95, no. 3, pp. 839-850, May/June, 1976.

"Compressor energy storage system could lead to wind power on demand", Professional Engineering, vol. 21, no. 4, pp. 42, 2008.

Ricardo is working with American firm General Compression to overcome the problems of wind power intermittency, developing a storage system it reckons can offer "wind on demand". The Dispatchable Wind system under development uses a compressor-based energy storage concept that could act as a buffer for windfarm output peaks. General Compression felt none of the then-available compressor technologies met the combination of performance, cost; power density and reliability requirements identified. So, with the help of Ricardo, it set about developing the Dragonfly high-power density compressor. Ricardo's Wave software simulated the complete system of four compressor stages and associated manifolds, ducting and intercoolers installed in the nacelle.

"Dinorwig Pumped Storage Hydropower Plant – The Perfect Complement to Britain's Nuclear Power", Modern Power Systems, pp. 64-77, May 1984.

"Energy Storage: Disempowered", The Engineer, pp. P.24-P.29, 2004.

The Regenesys energy storage system is in limbo after its new German owners pulled the plug when it was on the very brink of commercialisation. The move is a severe blow to the UK's position in what could prove a significant emerging area of power technology. It also raises wider questions over the commercial viability of energy storage, seen by many as a key component of future power networks that will make greater use of renewable energy sources. Regenesys was designed to act as an 'electricity warehouse', allowing power to be stored when usage is low and released into the network at times of peak demand. It also offered a potential bulwark against unexpected failures of the national power network by piping emergency electricity to local users while supplies are restored. RWE said its decision arose from a 'shift in strategic focus' that will see it concentrate on its core power generation and sales operations.

"Energy Storage Projects Take Large-Scale Approach", Plant Engineering, vol. 59, no. 12, pp. P3, 2005.

No longer relegated to backup status, energy storage technologies are expanding into grid-connected applications for peak shaving and frequency regulation. Two recent projects illustrate how energy-storage products are gaining respect as distributed energy resources. Columbus, Ohio-based utility American Electric Power will be installing a 1.2-MW stationary sodium-sulfur battery-based system at a substation owned by its Appalachian Power operating unit. Meanwhile, Beacon Power is now building a second Smart Energy Matrix for the New York State Energy Research and Development Authority, with plans for winter 2005 delivery.

"E.ON works on 1 MW storage for renewable energy supplies", Professional Engineering, vol. 20, no. 17, pp. 4, 2007.

Engineers at power firm E.ON are developing a 1 MW energy storage device that could help to overcome intermittency problems associated with renewable sources such as wind and solar. The device would essentially act as a giant battery storing energy when it is not needed and releasing it when demand is high. One of the biggest problems with the device would be its size. Once E.ON completes its tests and evaluation of the smaller test batteries, the larger prototype will be built.

"European Pumped Storage Practice – A Comparison of the Vianden Pumped Storage Scheme on the River Our in Luxembourg and the Ffestiniog Scheme in North Wales", World Power Engineering, vol. 1, pp. 22-29, November 1962.

"Feasibility Assessment of Customer-Side-of-the-Meter Applications for Battery Energy Storage", Report EM-2769, EPRI, December 1982.

"Foyers pumped-storage scheme", Water Power, vol. 20, pp. 87-88, 1968.

"Foyers pumped-storage scheme", Water Power, vol. 20, pp. 124-125, 1968.

"General Report of CIGRE Study Committee 11", Electra, no. 37, p. 61, 1974.

"High power inverter-fed motors operating at frequencies greater than 50 Hz or 60 Hz", CIGRE Working Group 11.06, Electra, no. 96, pp. 93-99, 1984.

"IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters", IEEE Standard 519-1992, The Institute of Electrical and Electronics Engineers, New York, 1992.

"IEEE Guide to the Collection and Presentation of Electrical, Electronic and Sensing Component Reliability Data for Nuclear-Power Generating Stations", IEEE Std 500-1984, Wiley Interscience, New York, 1984.

"Orlando Energy storage tank takes heat off of chillers", Power Engineering, vol. 107, no. 3, pp. 11-12, 2003.

The Orange County Convention Center in Orlando, Fla., which hosts POWER-GEN International every other year, has been in the throes of an impressive expansion project the past few years. When completed this year, the OCCC North/South Complex will add just under one million square feet of exhibition space to the existing 1.1 million square feet in the West Complex. However, the heat generated by Florida's weather, coupled with the heat generated by the hundreds of thousands of people visiting the new complex, will place prodigious demands on the center's cooling capabilities. Rather than add new chillers to meet the cooling demand from the new North/South Complex, OU Cooling is installing a thermal energy storage (TES) tank that will enable the existing water chillers to operate during off-peak hours while the TES tank is charging, shifting approximately 15 MW of electricity demand for air conditioning from on-peak to off-peak hours.

"Power Systems for Small Underwater Vehicles", The MIT/Marine Industry Collegium Held in Cambridge, Massachusetts on October 5-6, 1988, MITSG-88-11, 1988.

A two-day workshop will be held on power systems development in light of the fact that no one power system will solve the needs for all small underwater vehicles, i.e., swimmers, autonomous, and remotely operated underwater vehicles (AUV/ROB). Traditionally, electrical storage batteries have been used almost exclusively to meet the energy needs of small underwater vehicles. Although these batteries are easy, relatively safe, and convenient to use, their size and weight severely limit the mission length for an underwater vehicle. New developments in power systems will enhance the designer's options to develop a vehicle to perform its mission be it; antisubmarine warfare, surveillance, pipeline inspection, cable laying or oceanographic data collection.

"Proceedings International Conference Batteries for Utility Energy Storage", West Berlin, Federal Republic of Germany, November 9-11, 1987.

"Proceedings Second International Conference Batteries for Utility Energy Storage", Newport Beach, California, USA, July 24-28, 1989.

"Report on large variable speed drives for industrial applications and power plant auxiliaries", CIGRE Working Group 11.06, Electra, no. 126, pp. 8-30, 1989.

"SFC proves versatile, reliable starter for large gas turbines", Turbomachinery International, vol. 34, no. 4, pp. 34-37, May-June 1993.

The advent of large European-designed gas turbines in the North American market has brought with it the static frequency converter (SFC) as a versatile and reliable alternative to the traditional diesel engine and electric motor starting systems.

"Survey of Arc-Furnace Installations on Power Systems and Resulting Lamp Flicker", AIEE Transaction, vol. 76, pp. 170-181, 1957.

"Survey of Pumped Storage Projects in the United States and Canada to 1975", IEEE Committee Report, IEEE Transactions on Power Apparatus and Systems, vol. PAS-95, no. 3, pp. 851-858, May/June, 1976.

"Survey of pumped storage projects in the United States and Canada to 1975", IEEE Committee Report, IEEE Trans. on Power Apparatus and Systems, vol. PAS-95, no. 3, pp. 851-858, May/June, 1976.

"Survey of the word's pumped storage stations", Water Power, vol.22, no. 3, pp. 96-101, March 1970.

"500-kW Lead-Acid Battery for Peak-Shaving Energy Storage Testing and Evaluation", Report EM-3707, EPRI, October 1984.