Power balance regulation at large amounts of wind power

Frequency control and international experience

Elforsk rapport 13:43

Lennart Söder and Camille Hamon

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Foreword

An increasing amount of wind power with its inherent stochastic variation in production poses new challenges to the operation of the power system.

One of these challenges is how to select resources of balancing power with constraints on power system stability. To look at methods for this, a PhD-project with extra support by post-doc Magnus Perninge was started as project V-305 within the Vindforsk III research program.

The PhD-project has now come to end of phase 1 with a licentiate thesis by the PhD student Camille Hamon under the supervision of Professor Lennart Söder at the Royal Institute of Technology, KTH.

In adapting the power system, exchange of experience from different countries is important. A task force with IEA Wind – Task 25, Design and operation of power systems with large amounts of wind power - has the role of enhancing this experience exchange. KTH is a part of this task.

This report contains a short popular description of the work and the results complementary to reporting from Task 25, the Licentiate thesis of Camille Hamon and articles produced by the team at KTH.

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Comments on the work and the final report have been given by a reference group with the following members: Katherine Elkington, Elin Broström, and Oskar Sämfors from Svenska Kraftnät, Fredrik Carlsson, Vattenfall, Kjell Gustafsson, Statkraft, Anders Nilsberth, Fortum and Anders Björck, Elforsk

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Sammanfattning

I varje kraftsystem måste en tillförlitlig kontinuerlig balans mellan produktion och konsumtion upprätthållas. Detta innebär att det måste finnas tillräckligt med reserver för att balansera förändringar i produktion och konsumtion. I ett kraftsystem med större mängder vindkraft kan dessa förändringar öka eftersom vindkraftens produktion är svår att prognostisera. Om vindkraftverken ska delta i effektbalanshållningen med kapacitet att ändra effekten efter konsumtionen måste de köras med mindre effekt än den man maximalt kan få vid en viss vindstyrka. Annars kan man inte reglera upp effekten när konsumtionen ökar. Det skulle då betyda att man spiller vind, som ju likt vattnet för vattenkraften inte kan lagras. Därför bidrar vindkraftverken normalt inte till kraftbalansen i systemet. Detta innebär att det blir nya utmaningar beträffande hur man använder och designar kraftsystemet när mängden vindkraft ökar.

Projektets första del är inriktat på metodutveckling för kontinuerlig drift av ett kraftsystem med stora mängder vindkraft. Den andra delen har riktats mot internationellt samarbete och erfarenhetsutbyte inom IEA Task XXV "Design och drift av kraftsystem med stora mängder vindkraft".

I den första delen av projektet, har en ny metod för att aktivera frekvensreserver utvecklats. I dagsläget, utan en noggrann metod, innebär osäkerheter som kommer från vindkraft, och elförbrukning att den systemansvarige måste lägga på extra marginaler för att beakta osäkerheten i de använda metoderna. Till skillnad från vad som görs i dag, tar den nya metoden hänsyn till osäkerheten som kommer från lasten och vindkraft för att välja det optimala sättet att aktivera frekvensregleringsreserverna. Som en följd av detta kommer marginalerna som krävs för att skydda systemet mot osäkerheten vara lägre, vilket leder till en mer effektiv användning av systemresurser i kraftsystem med stora mängder vindkraft.

Den andra delen av projektet gäller det internationella samarbetet om integrations-metoder för vindkraft. Arbetet har lett till en bättre förståelse gällande kvalitén på vindkrafts-prognoser, vanligt förekommande vindkrafts-variationer inom timmen samt utveckling av en metod för hur man designar en metod för studier av vindkraftsintegration.

Summary

In any power system there has to be a reliable continuous balance between production and consumption, and enough resources must be available in order to counterbalance changes in production and consumption. In a power system with larger amounts of wind power these changes can increase since wind power production is difficult to forecast. If wind power plants are to participate in balancing services, they must be set to produce less than they are able to in order to keep margins which can be used for up regulation. Margins are kept by spilling the wind, which cannot be stored. For this reason, wind power plants do not usually participate in balancing services. New challenges concerning how to operate and dimension the power system will therefore arise when the amount of wind power increases.

The first part of the project is directed towards method development of continuous operation of a power system with large amounts of wind power. A second part has been directed towards international cooperation and experience exchange within IEA Task XXV “Design and operation of Power Systems with large amounts of wind power”.

In the first part of the project, a new method for operating the frequency control reserves has been developed. As of today the uncertainty coming from wind power and load is not taken into account in the control schemes themselves, and additional margins must be added by the system operator in order to protect the system against these uncertainties. Unlike that which is done today, this method takes into account the uncertainty coming from the load and the wind power when choosing the optimal way of activating the frequency control reserves. As a consequence, the margins necessary to protect the system against uncertainty will be lower, allowing a more efficient use of the system resources in power systems with large amounts of wind power.

In the second part of the project the international collaboration concerning integration methods of wind power has led to an improved understanding of quality of wind power forecasting, common wind power variations within the hour as well as development of a method for designing a method for wind power integration studies.

Innehåll

1 Introduction

In any power system there has to be a reliable continuous balance between production and consumption, and enough resources must be available in order to counterbalance changes in production and consumption. In a power system with larger amounts of wind power these changes can increase since wind power production is difficult to forecast. If wind power plants are to participate in balancing services, they must be set to produce less than they are able to in order to keep margins which can be used for up regulation. Margins are kept by spilling the wind, which cannot be stored. For this reason, wind power plants do not usually participate in balancing services. New challenges concerning how to operate and dimension the power system will therefore arise when the amount of wind power increases.

The Vindforsk project V-305 "Power balance regulation and electricity markets" has consisted of two parts. One is a PhD project and concerns method development of continuous operation of a power system with large amounts of wind power. The other part has been directed towards international cooperation and experience exchange within IEA Task XXV "Design and operation of Power Systems with large amounts of wind power".

With the new method for continuous operation of the power system it is possible to estimate the system stability boundaries in a rational way. With the knowledge of these boundaries it is possible to decide how to select a certain tertiary bid in order to minimize the total cost of the system and maintain stability of the power system in a system with larger amounts of wind power.

The IEA Task XXV cooperation has led to increased knowledge in the area of intra-hour operation challenges, wind power forecast accuracy and method development for wind power integration studies.

In this report a general presentation of the results from will be given. Chapters 2 - 3 describe the results from the PhD project while chapters 4 - 6 presents the outcomes form the IEA collaboration. For technical details on the research the reader is referred to the licentiate thesis [1] and the other publications in Chapter 7.

2 Keeping the balance in the power system

Frequency control schemes are used to maintain the balance between production and consumption within the operating periods. Production is scheduled ahead of the operating period to meet the expected load. The latter is estimated with forecasts. Forecasts are also used to estimate how much wind power plants can produce. The offers submitted by the market participants depend on these forecasts. During the actual operating period, deviations between the actual load and the planned production occur resulting in imbalances between production and consumption. As will be seen, these deviations result in a change in frequency, which is undesirable for a secure and reliable operation because power systems are designed to work at a nominal frequency (e.g. 50 Hz in Europe and 60 Hz in the U.S.). Hence, the frequency should be kept within certain limits, and power reserves are assigned to meet these deviations. These reserves are activated by the frequency control schemes, which are usually divided in different layers, where each layer has a specific role and acts within a certain time frame. These layers can be classified into primary, secondary and tertiary control.

2.1 Real-time imbalances between production and consumption and net load

Two main sources of imbalances between production and consumption exist:

1. The production plans made ahead of the operating period are on an energy basis over the operating period. Deviations between the planned production and the actual load can therefore arise within the operating period on a power basis, as illustrated in the Figure below.
2. The second source of imbalance comes from forecast errors and unexpected events. Wind power producers submit their production offers based on wind forecasts, and the production is planned to meet the load based on load forecasts. Therefore, due to errors in the wind or load forecasts, there will be situations with deficit or surplus of production within the operating period. For example, if the wind is weaker than forecasted, wind power plants will produce less than planned. Furthermore, unexpected events such as outages in generators or lines also cause deviations from the plans. Trading on the intra-day market, which ends before the start of the operating hour, allows the players to take into account new information, such as updated power plant statuses or new load and wind forecasts. This helps reduce the deviations from the day-ahead plans. The remaining deviations have to be met by other production resources which are activated by the frequency control schemes.

The influence of load forecast errors is illustrated in Figure 1: the actual load (thick line) is larger than the forecasted one (dashed line). Due to the deviations described above, the production plan (horizontal line) is not optimally adapted to the actual load. The striped and dotted areas are the deviation between the production plan and forecasted or actual load, respectively. The difference between these two deviations corresponds to the additional use of frequency control schemes due to forecast errors. The effect of wind forecast errors is similar.

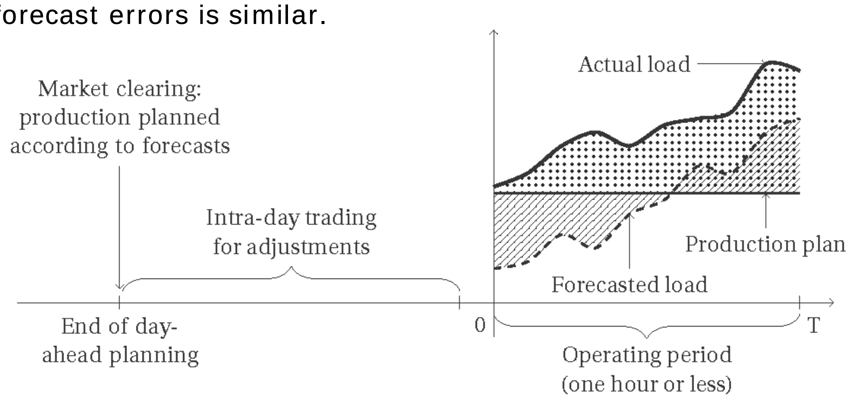

Figure 1: Influence of load forecast errors on frequency control schemes: the production is not planned optimally.

The additional reserve requirements put on load frequency schemes due to large amounts of wind power are then of interest. To study these additional requirements, net load is defined as the load minus the wind power production; that is, it is the load to be covered by the rest of the production fleet (not wind power). Figure 2 shows the load, wind power production and net load in Gotland, Sweden on 16 March 2009. By studying the net load forecast errors, the additional reserve requirements can be estimated. For details see [1].

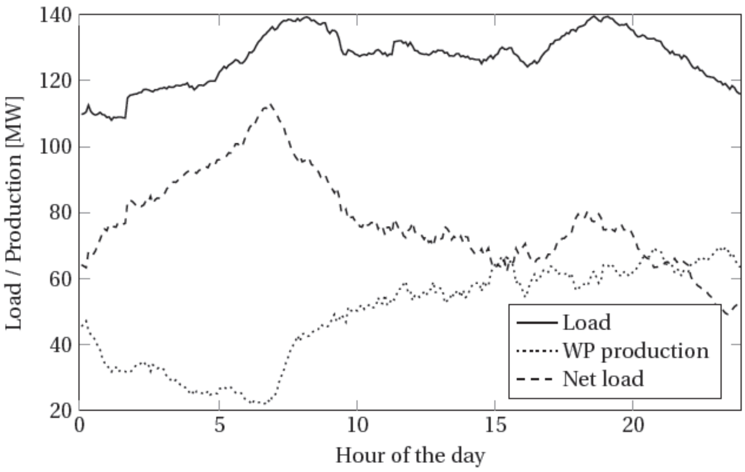

Figure 2: Load, wind power (WP) production and net load on Gotland, 16 March 2009, from Gotlands Energi AB (GEAB)

2.2 Primary control

Disturbances such as load variations or losses of generation units are translated in changes in frequency. In order to stabilize the frequency at a new value, primary control is used. The governing systems of the turbines driving the generators change the turbines' output power depending on the frequency deviation until either the balance between turbines' output power and the load is restored or the primary control reserves have been depleted.

The required change in power output as response to changes in frequency are defined in grid codes, and vary in different power systems. They are usually two types of primary control reserves: the first one is used for normal operations, that is, for small frequency deviations, while the second one is used when frequency deviations are larger, usually due to a large disturbance in the system such as the loss of a generating unit.

Primary control is termed "automatic active reserve" in Nordel. The frequency controlled normal operation reserve must be at least 600 MW and fully activated for frequency deviations of ±0.1 Hz. The frequency controlled disturbance reserve must be at least 1000 MW and fully activated at 49.5 Hz. Note that the latter starts being activated when the frequency falls under 49.9 Hz. The droop ρ can be defined as the ratio between the relative change in production and the relative change in frequency following this change in production. From the frequency stability standpoint, it is desirable to have a small droop because a disturbance would then lead to a smaller frequency deviation.

Primary control reserves must be activated within a time frame predefined in grid codes. For Nordel, this is two to three minutes for the frequency controlled normal operation reserve, and 30 seconds for the frequency controlled disturbance reserve. In UCTE, 50% of the primary control reserves must be activated within 15 seconds, and 100% within 30 seconds. Primary control restores the power balance between production and consumption, but does not restore the frequency at its nominal value.

The location of the primary control reserves is usually determined in the planning phase. For example, in Sweden, the balance responsible players willing to participate in primary control can submit bids to markets dedicated to primary control reserve for one day after and two days after the current day.

2.3 Secondary control

Secondary control reserves are automatically controlled reserves aimed at restoring the frequency to its nominal value and at relieving the primary control reserves to make them available when a new disturbance occurs.

In many countries, automatic generation control (AGC) is used for secondary control purposes. AGC is usually used for more than restoring the frequency to its nominal value. In continental Europe, for example, AGC is used to maintain the tie line interchanges at their contracted values. Hence, it measures two errors: the frequency deviation from its nominal value and the power interchange deviations from their contracted values. The sum of these two errors 3 is called "area control error" (ACE). The ACE is then processed by a central controller, usually a proportional-integral or purely integral controller, which computes the required change in production to bring these errors to zero. The change in production is then distributed among the participating generators, as a change in the load reference set point of their turbine governor. The distribution of the reserves among participating generators is done in the planning phase. Secondary control starts acting after primary control has been activated.

In UCTE, secondary control must be fully activated within 15 minutes. In Nordel, secondary control is not used as of today, but will be introduced under the name Load Frequency Control (LFC) in January 2013 [37]. The corresponding reserves are termed Frequency Restoration Reserves. The introduction of secondary control in the Nordic system was deemed necessary because the frequency quality has kept deteriorating over the past decade. Compared to what is done in UCTE, it will only be used to restore the frequency to 50 Hz because the Nordic system is handled commonly by the system operators, and, hence, is treated as one control area.

2.4 Tertiary control

Tertiary control refers to the manual activation of power reserves by the system operator.

In Nordel, tertiary control is the main tool to maintain the power balance as of today, since secondary control has not yet been introduced. Tertiary control is procured on the balancing market, where the power producers can submit regulating bids. If necessary, the system operators in the Nordic system can activate regulating bids, which are chosen depending on their price and location to avoid overloading transmission lines. Balancing bids must be activated within 15 minutes. In UCTE, tertiary control is used to relieve and support secondary control reserves.

Note that the term “secondary control” can be used to refer to tertiary control in Nordel (manual activation of balancing bids), although it does not work as the secondary control in UCTE (AGC). The term tertiary control is used throughout this work to refer to the manual activation of balancing bids. This thesis deals with tertiary control. In this work, a new method for re dispatching generation is proposed. An overview is described below and details are found in [1].

2.5 Summary

Frequency control schemes consist of different layers. In response to an event such as a load change or the loss of a generation unit, the frequency will change. The reserves dedicated to primary control will be automatically activated within a few seconds (and fully activated within less than two to three minutes) in order to stabilize the frequency at a new value, which results in a steady-state frequency deviation from the nominal value. The secondary control reserves will automatically react to this steady-state frequency deviation, and be activated in order to bring back the frequency deviation to zero and refill the primary control reserves. In some systems such as the Nordic system, secondary control has not been implemented yet. In other systems, secondary control also controls the generation to restore the tie-line interchanges to their contracted value. Finally, the tertiary control will act in order to relieve the secondary control reserves.

The purpose of this project is to develop tools for the optimal operation of frequency control schemes under uncertainty coming from larger amounts of wind power. In the following, the focus will be put on the operation of the tertiary control schemes, that is, on the optimal manual activation of balancing bids. “Optimal” means here that the power plants participating in tertiary control must be re-dispatched at as low cost as possible while maintaining a secure operation of the power system. Hence, the problem to be solved is the following:

$$\begin{aligned} &\min \quad \text{re-dispatch cost} \\ &\text{s.t.} \quad \text{system is operated securely} \end{aligned} \tag{1}$$

Today, operating the system securely is usually understood in the sense of the N-1 criterion which stays that the system must remain stable after the loss of a critical component[1]. To fully understand this criterion, concepts of power system stability must therefore be introduced.

[1] A critical component can for example be an important transmission line or a large generation unit, such as a section of a nuclear power plant.

3 Considering stability limits in power system operation

3.1 Stability limits

When the loading in the system increases, the power transfers across the electrical grid increase. As a consequence, the power system becomes more stressed. If the loading increases too much, stability issues can arise. Examples of stability issues are:

- Voltage stability issues (falling bus voltages possibly leading to voltage collapse).
- Small-signal stability issues (the system is unstable for small disturbances).
- Line thermal limits (transmission lines reaching their thermal limit when the power transfers across them increase too much).

Hence, stability limits can be defined as the maximum loading before the system becomes unstable. Formally, we define stability limits as follows. Consider a power system with m load locations, and a base case loading at these locations. Let $\zeta_0 \in \mathbb{R}^m$ denote this base case loading. Let $d \in \mathbb{R}^m$ define a direction of load increase, i.e. a way of increasing the loads at the m locations. The new loading after an increase s from ζ_0 in this direction d is then $\zeta = \zeta_0 + sd$. Thus, s defines how much the loads increase in the direction d from the base case loading. As explained above, as the loading increases (i.e. as s increases), the power system becomes more stressed. Eventually, a critical loading will be reached beyond which the system becomes unstable. A critical value $s_{\lim}$ can thus be defined, corresponding to the critical loading $\zeta_{\lim} = \zeta_0 + s_{\lim} d$. The stability limit in the direction d of load increase is exactly this critical loading $\zeta_{\lim}$. It is important to note that different directions of load increase lead to different value of the stability limit. Also, as stated above, difference types of stability limits exist (stability limits corresponding to voltage stability, small-signal stability, line thermal limit, …). The stability limits are sometimes called loadability limits, and these terms will be used interchangeably.

In Sweden, Svenska Kraftnät, the Swedish transmission operator, computes transmission limits for the three (currently) main bottlenecks by using a model of the Swedish power system, simulating a contingency in it and virtually increasing power transfers across the bottlenecks in this model until the loadability limits, corresponding to the maximum possible power transfers before voltage stability issues arise, are hit. A margin (TRM = Transmission Reserve Margin) is then subtracted from the computed loadability limits to set the transmission limits, which define the maximum allowed power transfers across the corridors. If the power transfers come close to these transmission

limits, the system operator must act, for example by manually activating frequency control reserves (balancing bids in the case of Sweden).
The same concepts apply with wind power in the power system, except that "net loading" is substituted for "loading", as already described in Section 2.1. As it was the case when only considering the loading, increasing the net loading too much in some direction will eventually make the system unstable. Hence, stability limits can be defined in this case as well.

3.2 The stability boundary

When considering all stability limits in all possible load increase directions, the stability boundary can be defined as the set of all these stability limits. Figure 3 illustrates the concept of stability boundary in a fictitious power system with two net load locations, where ζ_1 and ζ_2 are the net loadings at these locations. The stability boundary is the blue curve. Two stability limits (i.e. points on the stability boundary) are shown. They can be computed as explained in Section 3.1: from the current operating point (corresponding to a certain value of the net loading), the net loadings at the two locations are increased in the directions d_1 and d_2 until the system becomes unstable, which corresponds to reaching the stability boundary.

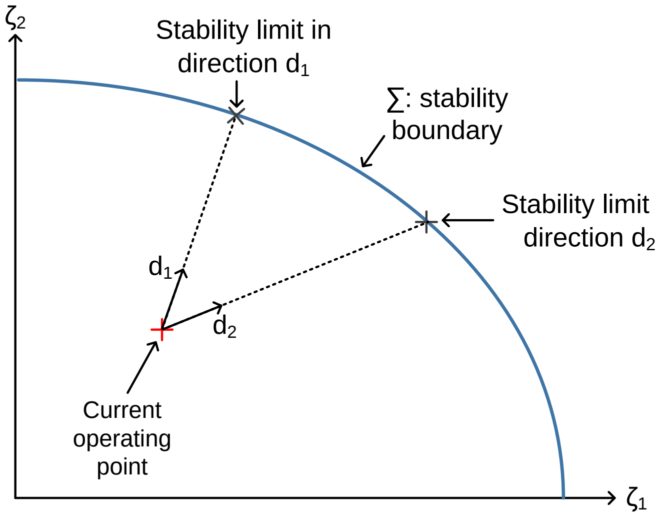

Figure 3: Stability boundary and stability limits.

When a contingency[2] occurs, the power system becomes more stressed. Intuitively, this means that the stability limits should change. Compared to the pre-contingency case, the post-contingency stability limits correspond to lower net loadings, because the system can be loaded less before it becomes unstable. Figure 4 illustrates this. The blue curve is the pre-contingency stability boundary. After a contingency happens, it shrinks to the red curve, which is the new valid stability boundary for the post-contingency system. Three loading increase paths are shown in the figure. If no contingency has occurred, the net loading can increase up to the blue stability boundary (the

[2] A contingency can be, for example, the loss of a transmission line or of a generation unit.

pre-contingency stability boundary) while it can only increase up to the red stability boundary (the post-contingency stability boundary) after the contingency has occurred. This illustrates that the system becomes more stressed after a contingency happens.

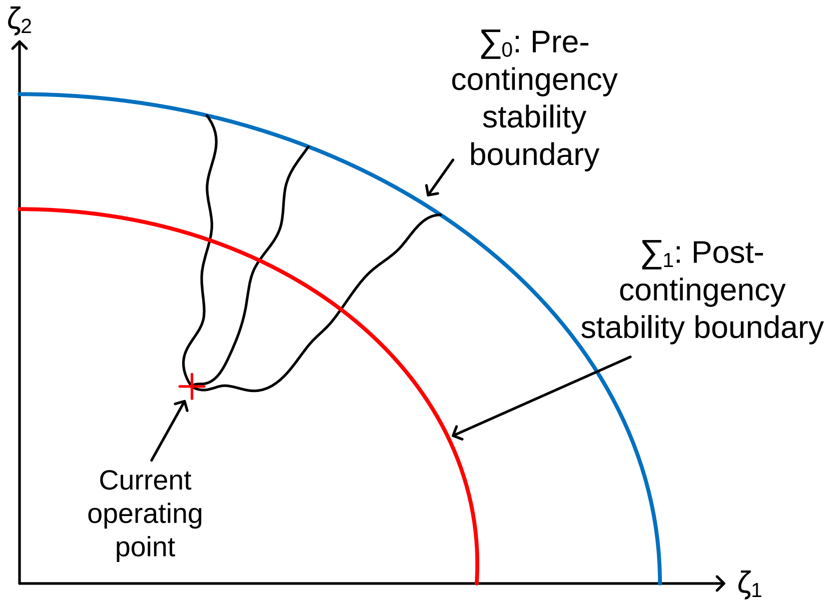

Figure 4: Effect of a contingency on the stability boundary.

Other parameters influencing the shape of the stability boundary are the active power generation of the power plants. Suppose for example that a power plant (PP1) close to some load starts producing more, thus relieving part of the production coming from another power plant (PP2) located farther away from the load. Since the production in PP2 decreases, the power transfer from PP2 to the load decreases also. Hence, the power system becomes less stressed by moving the generation to PP1 which is located closer to the load than PP2. This means that the stability boundary will be located farther away from the current operating point.

The impact of different active power levels is important because the transmission system operator can change these generation levels by activating some balancing bids when operating the tertiary control scheme.

Recall the problem in Equation which must be solved to optimally operate the tertiary frequency control schemes: the generation levels must be set so as to minimize the cost while operating the system securely. From the study of the stability boundary, “operating the system securely” means that the system must be inside the stability boundaries, for all considered contingencies.

3.3 Challenges with larger amounts of variable resources

The stability boundary is needed by system operators to both monitor power systems and take optimal actions if necessary to ensure an adequate level of system security. It is, however, not trivial to estimate the stability boundary. Rather, points can be computed on it in different directions in parameter space as was seen above.

As of today, it has been possible to predict relevant directions, and compute the stability limits in these directions, because the main source of variations in parameter space were the loads, and accurate load forecast methods exist. The expected large amounts of variable resources such as wind power in future power systems will introduce new sources of variations. It becomes more relevant to consider the variations in net load, which is the part of the load not covered by these variable resources. As of today, wind power forecasts are not as accurate as load forecasts. Hence, it becomes all the more challenging for system operators to choose relevant net load increase directions in parameter space.

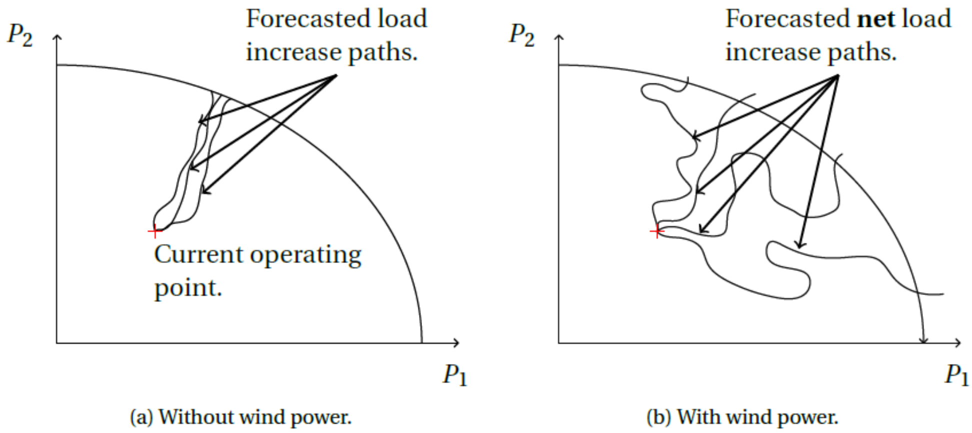

Figure 5: Two dimensional stability boundary of a fictitious power system, and forecasted load increase path (system without wind power) and net load increase path (with wind power). P1 and P2 are the net loads at locations 1 and 2, respectively.

Figure 5 depicts the situation. A two-dimensional stability boundary in a fictitious power system is shown. The figure on the left-hand side shows a few possible future load increase paths in this power system, determined by forecasts. The variations in forecast are not large. Hence, the load forecast errors are small. The figure on the right-hand side shows what happens in the same system when large amounts of wind power have been installed. Net loads are considered instead of loads, and the figure shows that since wind power cannot be forecasted as accurately as loads, the expected variations (or forecast errors) are larger. In such a system, identifying relevant directions in to look for stability limits is challenging.

Therefore, as the amount of variable resources increase, there is a need for considering more operating situations (such as load increase paths) than before. Because power systems must be operated in a secure way, this entails a need for knowing larger parts of the stability boundary. This could be achieved by computing a larger number of stability limits, in many possible load increase directions. However, the task of computing stability limits is computationally demanding. For example, a good knowledge of the entire stability boundary for a small 3 load system (IEEE 9 bus system) can be obtained by computing 10 000 stability limits, which required several hours on a modern computer. Therefore, computing more stability limits does not seem to be an adequate method to deal with the larger variations coming from variable resources.

3.4 Proposed solution

Since having an exact knowledge of the stability boundary is not practically possible, it is proposed in this work [1] to use local approximations of the different smooth parts of the stability boundary. The computation of local approximations is not time demanding, and they can be used to approximate the actual stability boundary. The proposed approximations are second-order Taylor expansions. Since these are local approximations, they are computed around a certain "approximation point". The closer to this approximation point, the better the approximation will be. Hence, the choice of the approximation point at which the second-order approximations are computed affects the accuracy of the approximation. An algorithm was developed in order to find the most likely point on each smooth part, the likeliness being given by forecasts. These most likely points are then used as approximation points. The accuracy of the approximation is assessed in Section 3.5 "Results".

With this new method it is possible to estimate the stability boundaries in a rational way. With the knowledge of these boundaries it is possible to decide how to select a certain tertiary bid in order to minimize the total cost and keep the stability of the power system in a system with larger amounts of wind power.

3.5 Results

The IEEE 9 bus system in Figure 6 is considered. It consists of three loads and three generators.

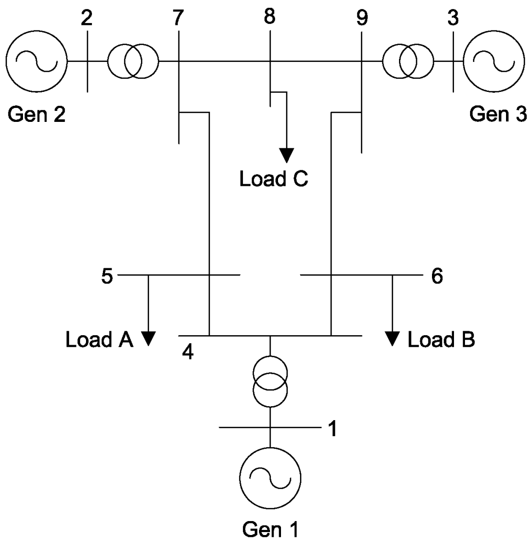

Figure 6: IEEE 9 bus system.

In order to compare the second-order approximations with the real stability boundary which is approximated, the latter is determined by computing many points on it. This is a very time-consuming process (it takes about 10 hours on a modern computer). The obtained stability boundary (the set of all computed points) is shown in Figure 7. This is a three-dimensional surface because the system in Figure 6 has three loads. The different colors correspond to different stability issues (voltage stability, small-signal stability or line thermal limits) which can arise.

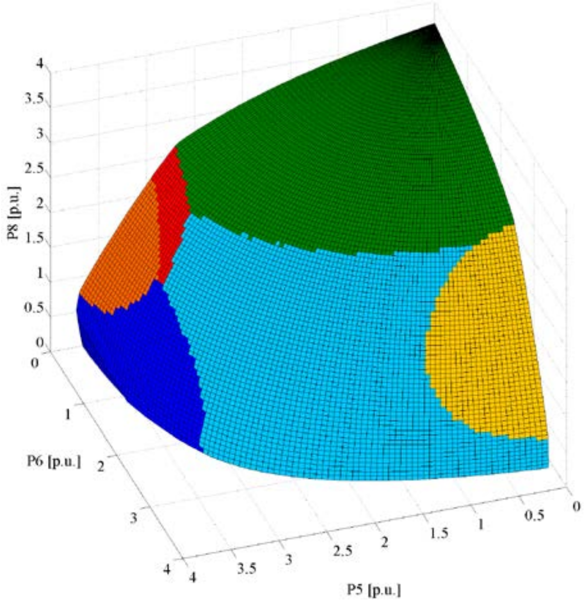

Figure 7: Stability boundary of the IEEE 9 bus system.

Second-order approximations were computed for each colored part of the actual stability boundary of Figure 7. About one minute for each part was necessary to carry out this computation. Then, their accuracy was assessed in the following way:

1. Each point on the surface of Figure 7 is parameterized by two angles: one for the vertical displacement and one for the horizontal displacement (the so-called "polar" and "azimuthal" angles used in the spherical coordinate system).
2. The distance from each of these points to the closest second-order approximation is computed.
3. The distance divided by the value of the loading at the corresponding point on the actual surface is plotted, for all points, against the two angles parameterizing the points.

The plot of all distances is shown in Figure 8. The colors on the graph correspond to the color from Figure 7. For example, the green part in Figure 8 shows the distance between the green part of Figure 8 and its approximation. Since the distances are normalized by dividing by the value of the loadings on the actual surface, the z axis shows a per unit error.

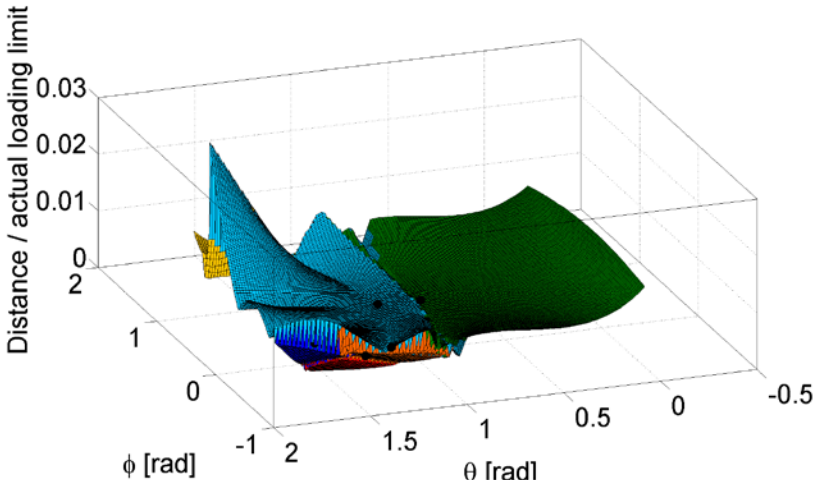

Figure 8: Distances between each point on the actual stability boundary and the second-order approximation.

It can be seen that over the entire surface, the error is less than 2.5 %. The light blue peak where the largest errors are located corresponds to the bottom right-hand corner of the surface in Figure 7 which is far away from the approximation point around which the second-order approximation was computed. As discussed in Section 3.4, the farther away from the approximation point, the less accurate the approximation is expected to be, which is why the error gets larger in the region of the light blue peak. Note that by the way in which the approximation point is chosen, it is very unlikely that the net loading will be located in this part of the surface (the approximation point was chosen as the most likely point on the stability surface as was explained in Section 3.4).

It can therefore be concluded that the second-order approximation approximates the real stability boundary with a good accuracy.

4 Experience and challenges with short term balancing in systems with large penetration of wind power

4.1 Intra hour wind power variation

In countries as Ireland, Portugal, Spain, Germany, Denmark and parts of Sweden there is experience of how common wind power changes of different sizes are. The size of the changes depends on meteorology, the amount of wind power and how spread the wind power installations are. The size of the changes also depends on how long period one studies. The variation within 30 minutes is larger than variation within 5 minutes.

A summary of the result from the different countries is shown in the figure below.

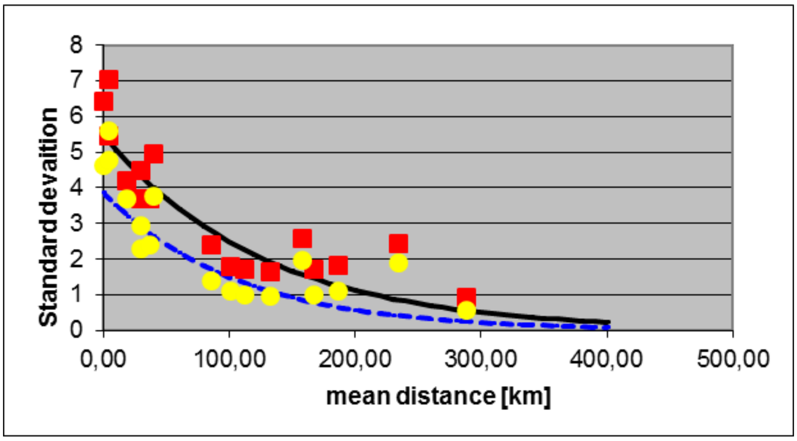

Figure 9: Standard deviation in percent of installed capacity for 15-minute (circles), 30-minute (boxes), 10-minute fitted (dashed), and 30-minute fitted (solid line) change of total wind power as a function of mean distance between all wind power stations.

One example in the figure is Gotland with 110 MW of wind power capacity. Studied wind power data consists of a total of 27411 five-minute measurements of both the load and the wind power production on Gotland, Sweden under the period March 12 – June 16, 2011. 85 percent of all wind power production is measured while 15 percent is estimated from nearby units. The mean wind power production during this period was 26,8 MW, i.e. 24 percent of installed capacity. The standard deviation (as percent of installed capacity) for the three studied time periods were 1,41% (5 min), 2,94% (15 min) and 4,48% (30 min). With an assumption of approximate Gaussian distributed changes then 32 percent is outside ± σ and 0,3 percent is outside ± 3σ. This means, e.g., that during 99,7 percent of the time the wind power changes within 30 minutes are lower than 13,43 percent of 110 MW, i.e. 14,8 MW. The wind power on Gotland is rather much concentrated to a limited area of the south-west cost of the island. The mean distance between all wind power plants is estimated to 30 km. So Gotland is in the figure represented with mean distance 30 km and the two standard deviations 2,94% (15 min) and 4,48% (30 min).

In the figure the measuring points are also fitted (least square method) to the curve

$$\sigma = \sigma_0 \cdot e^{-p \cdot dist} \quad (2)$$

where

σ_0 = standard deviation for wind power in one location

p = parameter

dist = mean distance between the wind power units in km.

This curve type is selected since it is reasonable that it starts on a certain point at distance = zero, and that it decreases but not to zero.

With the same weight to all points, the resulting parameters for the curve drawn in the figure are shown in the table.

parameter	15 minute	30 minute
σ_0	4,67	5,85
p	0,0106	0,00799

Table 1: Least square parameter for fitting of standard deviations to a decreasing function.

4.2 Experience of handling of large share of wind power

Portugal had in March 2011 4229 MW of wind power installed. The minimum and maximum loads were 3380 MW and 9400 MW respectively and the only interconnection capacity is to Spain, 1200 MW. During 2010, 17 percent of the energy consumption in Portugal was covered by wind power. On May 15 2011, an extreme penetration period was observed at 6h45 with wind ensuring 81% of the consumption. Most of the hydro generation (with dams) halted generation between midnight and 4 a.m. staying only Tabuaço, Cabril and Bouça in operation. Close to the wind peak penetration, a few other hydros (Venda Nova, Tabuaço and Raiva) contributed with generation to balance the wind power fluctuations while reversible hydro centrals as Aguieira and Alqueva were using all their pumping capacity.

Situations with high penetration has also occurred in, e.g. Spain (53,8%) and Ireland (52%). For more details, see reference [3].

5 Wind power forecasting accuracy

Wind power forecasting is expected to be an important enabler for greater penetration of wind power into electricity systems. Since no wind forecasting system is perfect, a thorough understanding of the errors that do occur can be critical to system operation functions, such as the setting of operating reserve levels. Because of this a comparison has been made concerning forcast accuracy in different countries.

For Sweden, Svenska Kraftnät makes wind power forecasts for whole Sweden. The day-ahead forecasts for the Swedish system (year 2011) include 2,899 MW of installed wind capacity. The distribution of forecast errors shown in the figure below shows a slightly negatively skewed leptokurtic distribution. The Swedish errors are interesting for their fairly small spread, with the largest errors being less than 30% of the installed wind capacity. This is likely due to the large amount of geographic diversity stemming from the siting of the Swedish turbines over a large geographic area. It is also interesting to see that the normal distribution would under-represent the negative error tail, but over-represent the positive error tail, because of the skewness of the distribution.

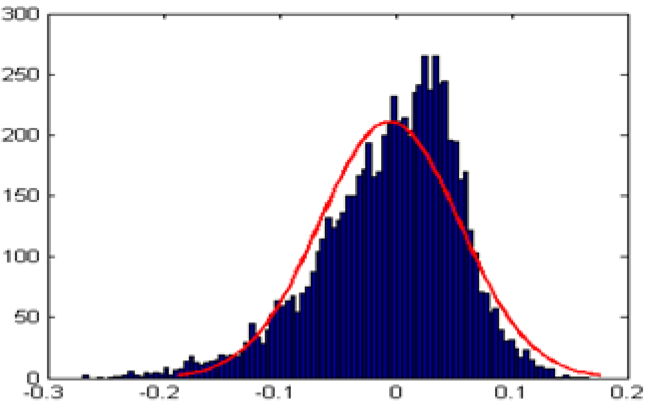

Figure 10: Histogram of the normalized day-ahead forecast errors for the Swedish system. μ = -0.0052; σ = 0.0603; γ = -0.7252; κ = 0.7757. The red line represents a normal distribution with the same mean and standard deviation.

As a comparison one can show the result for Germany, see below. The German data is from the year 2010 and covers the total installed wind capacity in Germany ranging from 25.18 GW in January 2010 to 26.39 GW in December 2010. The power measurement is based on an up-scaling algorithm based on spatially distributed reference wind farms that include about 25% of the total capacity. The forecasts are used and published by the German TSOs and are based on combinations of power forecasts from different providers and on different NWP models. The day-ahead forecasting errors have a slightly negative skew, and are leptokurtic.

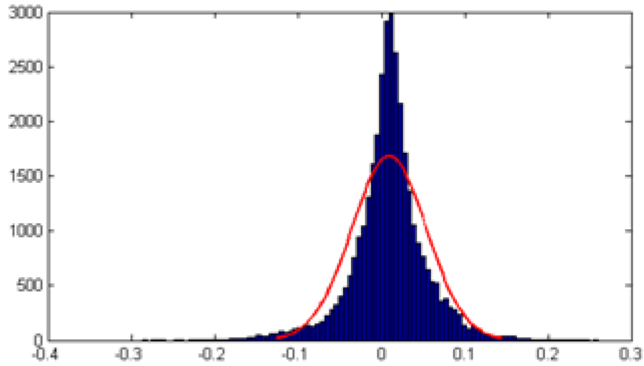

Figure 11: Histogram of the normalized day-ahead forecast errors for the German system. μ = 0.0092; σ = 0.0450; γ = -0.2891; κ = 3.5896. The red line represents a normal distribution with the same mean and standard deviation.

It can be seen that it may be possible to improve the Swedish day-ahead forecasts since the current standard deviation in Sweden is around 6% of installed capacity while it is 4,5% in Germany. For more details of the comparison, see ref [7], while more details concerning the Swedish forecasts are found in [10].

6 Wind power integration studies

There have been many wind integration studies in recent years, with evolving methodologies. Since power systems and data availability vary significantly, the results and methodologies used in these studies have varied accordingly. Within the international collaboration under IEA WIND Task 25 there is a continuous work towards Recommended Practices for Wind Integration studies. An overview of a complete wind integration study is presented below as a flow chart. The set-up of a study and the main assumptions has a critical impact on the results. The recommendations are applicable for other variable renewable sources, including photovoltaics.

A wind integration study usually begins with a set of input data characterizing wind power and the underlying power system along with a wind power penetration level that is of interest (the blue boxes).

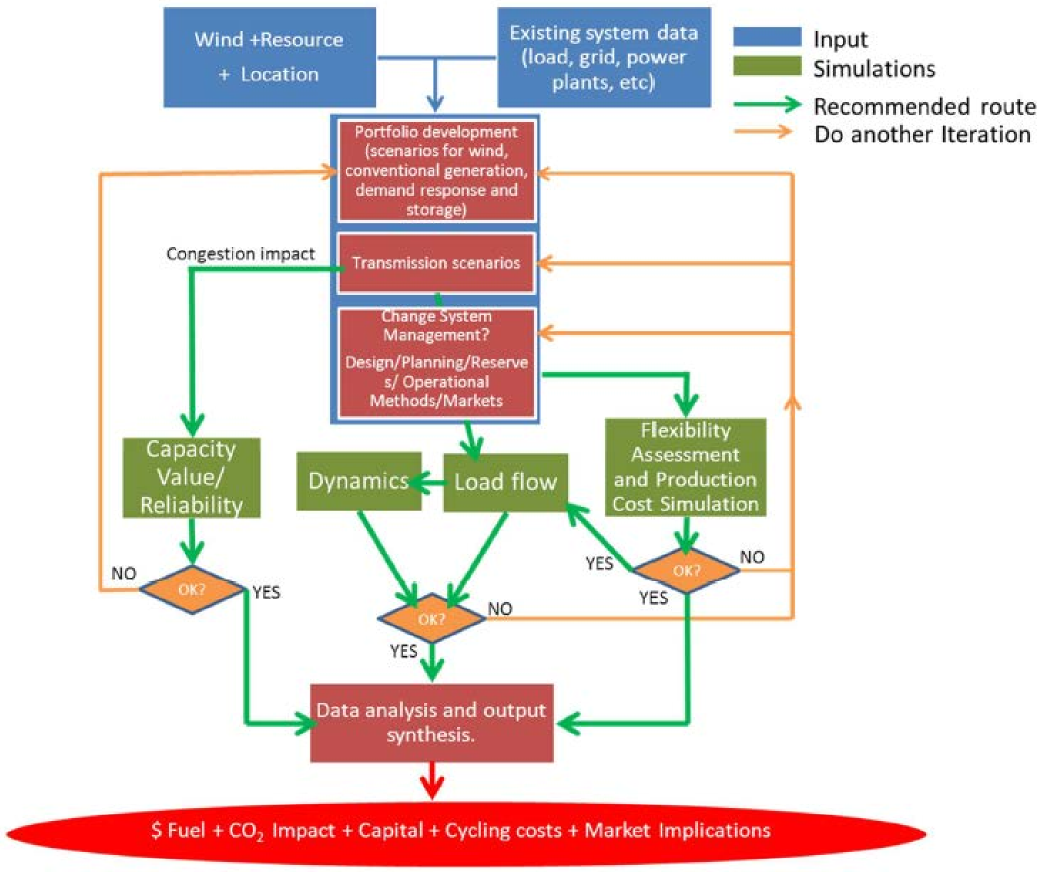

Figure 12: Wind integration study components. Flow chart showing a recommended route with iteration loops and possible routes when not all components are studied.

The electrical footprint must be chosen, which may include a subset of, or the entire synchronous system. Portfolio development needs to establish the kind of system that is studied – current or future system, assumed generation fleet, demand and flexibility options available. An important aspect is how wind power is added to the system; by replacing existing generation or by adding wind power to the existing system. Wind integration studies usually involve investigations of transmission adequacy, simulations of the operation of power plants in the system and calculations of the capacity needed to meet resource adequacy requirements in the peak load situations (the green simulation boxes). Grid simulations (load flow and dynamics) involve contingency analysis and stability studies. Dynamic simulations and flexibility assessment are necessary, especially when studying higher penetration levels of wind power.

Reliability constraints from transmission or capacity adequacy or reserve margins will require iteration on the initial results to adjust the installed capacity of the remaining power plants (the portfolio), the transmission grid, and the operational methods of system management (like reserves).

More details are found in [8] and [9] which is the final report from IEA Task 25 for phase two 2009-2011.

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