Power quality and system stability

Vindforsk projects, a survey of the development and research needs

Elforsk report 12:39

Morten Hemmingsson and Daniel Karlsson, Gothia Power AB, April 2012

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Preface

Vindforsk III is Swedish research program that is running in the period 2009-2012. The programme is divided into five activity areas:

1. The wind resource and external conditions.
2. Cost-effective plants
3. Operation and maintenance
4. Wind power in the power system
5. Standardization

In the preparation of a final report at the end of the program, and preparation of a new program period, work with survey reports for different research areas is being carried out. One such research area is “Power quality and system stability”.

Work with a survey report for this area is carried out by Morten Hemmingsson and Daniel Karlsson from Gothia Power.

The report contains descriptions of projects within the program; the status and trends of technology and research; and finally an analysis of research needs within the area.

Conclusions and opinions in the report are those of the authors.

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Summary

This report provides a survey on seven research projects, funded by Elforsk/Vindforsk. Each project is focused on a specific issue, related to wind power integration and power quality or power system stability, and states technically possible solutions or describes technical phenomena. Trends and development in the area of power quality and system stability are then reviewed and summarized and finally future research needs are identified.

Three out of the seven projects are "research" projects that can be expected to deliver results on why things are as they are or how things should be done.

- V-306, Harmonic distortion and wind power installations
- V-311, Assessment of the dynamic impact of large wind parks on the power system stability
- V-369, Power system stability and grid code requirements relevant for large-scale wind power integration

One project explains the issue of subsynchronous resonance and how to possibly avoid it.

- V-309, The impact of wind farms on subsynchronous resonance in power systems

Two projects resulted in survey reports, which describe design principles, possible problems with today's setup and suggest studies that should be done in order to get a better understanding of why the problems appear.

- V-339, Problems in the power system related to wind power, an inventory
- V-340, Perspectives on power electronics and grid solutions for offshore wind farms

One project describes power quality measurements from the 110 MW Lillgrund wind power farm, in the 130 kV grid connection point.

- V-354, Power Quality in the 130 kV connection point of a 110 MW wind farm

The general trends concerning wind power integration is towards larger turbines, larger farms, and clusters and cluster integration. The fraction of wind power generated electricity in the power systems around the world will increase, and wind power control and ancillary services will become a major issue for stable power system operation. A list of major research projects and research groups in the area of wind power and power quality or system stability are also listed in this report.

Issues related to the increased size of wind power installations, increased contributions to the total electricity generation from wind power, grid code development and harmonization, wind power generation control and ancillary services, and fault clearance in wind power dominated systems, will be main targets for the near future research efforts.

References from the authors of the seven reports are listed and commented.

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1 Projects within Vindforsk III

1.1 About the Vindforsk programme 2009-2012

Vindforsk III is a co-financed research programme that provides funding for basic and applied wind energy research. The Swedish Energy Agency is financing 50 percent of the costs within the programme, and the other half is financed by energy companies and other companies with connection to wind power. The programme total budget is 80 million SEK over a four-year period.

The overall objective of Vindforsk is to strengthen the conditions for building and operating wind power by:

- producing generalizable results concerning wind energy characteristics and opportunities
- conducting research at the international forefront within a number of technology areas to preserve and strengthen the skills of existing research groups at universities and engineering consultants
- strengthening the recruitment base for Swedish wind power industry
- making wind energy research visible and disseminate its results

The programme is divided into five activity areas:

1. The wind resource and external conditions
2. Cost-effective plants
3. Operation and maintenance
4. Wind power in the power system
5. Standardization

1.2 Vindforsk projects within the research area of power quality and system stability

Within the activity area "Wind power in the power system", one sub-area for projects is "Wind energy in the power system - Power quality and system stability". The goal for this sub-area is to build up knowledge and competence that aids when integrating wind power in the power system. Based on needs from the financers of the program, projects according to Table 1 have been started.

Project number	Project title	Project leader	Financing
V-306	Harmonic distortion and wind power installations	Math Bollen, Luleå Technical University	SEK 1 750 000 cash funding and SEK 550 000 in kind
V-309	The impact of Wind Farms on Subsynchronous Resonance in Power Systems	Evert Agneholm, Gothia Power	SEK 500 000 cash funding and SEK 200 000 in kind
V-311	Assessment of the dynamic impact of large wind parks on the power system stability	Mehrdad Ghandhari, KTH	SEK 1 875 000 cash funding
V-339	Problems in the power system related to wind power, An inventory	Daniel Wall, Vattenfall Research & Development	SEK 200 000 cash funding
V-340	Perspectives on Power Electronics and Grid Solutions for Offshore Wind farms	Hans-Peter Nee, KTH	SEK 200 000 cash funding
V-354	Power Quality in the 130 kV connection point of a 110 MW wind farm	Urban Axelsson, Vattenfall Research and Development	SEK 720 000 cash funding and SEK 100 000 in kind
V-369	Power system stability and grid code requirements relevant for large-scale wind power integration	Nayeem Ullah, STRI AB	SEK 1 634 000 cash funding

Table 1 Vindforsk projects within the sub-area "Power quality and system stability".

1.2.1 Harmonic distortion and wind power installations (V-306)

Harmonic waveform distortion has been an issue in the design of power systems for more than 100 years now. But it did not become a serious research subject before the introduction of HVDC and large industrial converters, starting in the 1960s. The work done by Jos Arrillaga and others should certainly be mentioned here.

Harmonic resonances have been a known and well-studied subject for many years now and are discussed in several textbooks. However, as experience shows, harmonic resonances are not always considered in the design of new installations. Further, resonances in association with wind power might introduce a number of new phenomena. At first, low resonance frequencies (350 Hz or lower) are still very uncommon at subtransmission and transmission level. The amount of damping is likely to be significantly different than at distribution level, where resonance frequencies down to 250 Hz are more common. Preliminary studies in Denmark have shown that resonance frequencies as low as 150 Hz are possible. There is no experience with such resonance frequencies at all. In the collection grid of a wind power park, the amount of damping may be very small, so that resonances could result in very high voltage and/or current distortion.

Modern power-electronic converters, like the ones used in wind turbines with DFIG or full-power converter, show a completely different spectrum. Contributing factors to the spectrum are the switching frequency, resonances associated with any harmonic or EMI filter, and variations in converter performance (like switching frequency) during the course of a 50 Hz cycle. However, no clear knowledge exists on the waveform distortion due to wind turbines with power electronic converters, nor exists any general method to describe this distortion.

Methods have been developed at Luleå University of Technology to analyse the spectrum of active converters in the frequency range starting at about 1 kHz. These methods are based on the time-frequency plot or spectrogram where the variations in spectrum are given with a high time resolution, significantly less than 1 cycle of the power system frequency.

Goal of the project

The main academic objective of this project is to obtain deep understanding of voltage and current distortion associated with wind power installations. This should in turn result in technical publications and world leading expertise and knowledge.

The specific results to be obtained from the project include:

- Methods for evaluating the impact of individual installations on waveform distortion.
- A quantification of the impact of large scale wind power integration on waveform distortion in transmission and distribution networks.
- Methods for measurement of waveform distortion in association with wind power installations and for the presentation of the measurement results.
- Future harmonic levels in subtransmission and transmission networks.

Practical applications of the research results from this project include design rules for large wind parks; design of harmonic filters with wind turbines; setting of limits for harmonic emission at higher frequencies; methods for presenting the results of harmonic measurements; planning levels for harmonic emission. The project will cover both low frequency harmonics (up to about 2 kHz) and high frequency harmonics (about 2 kHz and above).

Already obtained results

Measurements have been performed at five different windparks in the north of Sweden, in the frequency range up to 2 kHz. In all cases the parks were equipped with power electronic based turbines (DFIG and full-power converter). The spectra of the emission from individual turbines show a combination of discrete frequency components and continuous emission over a wider frequency range. Overall, the emission from the turbines is small, up to about 1% of the rated current.

The discrete frequency components are mainly found at the characteristic harmonics of a six-pulse converter. These components, although often dominating the spectrum, are much smaller than those from typical industrial installations or from domestic or commercial buildings. The continuous emission and some of the discrete components are found at non-characteristic harmonics (like even harmonics) and at interharmonic frequencies. Those components are larger than the typical emission from other installations or buildings.

When considering the impact of the emission on the grid, the minimum short-circuit ratio has been calculated that is required to keep the voltage distortion below permissible levels. The higher this short-circuit ratio, the higher the impact on the grid. It has been shown that the main impact takes place for interharmonics and not for harmonics.

Theoretical studies have been made of the occurrence of resonances in the wind park. Both series and shunt resonances can occur resulting in higher emission at the park-grid interface than would be expected from the emission of the individual turbines. It is shown that the resonance frequency is strongly dependent on the number of components present in the supply to the wind park, e.g. the outage of a grid transformer will cause a large change in the resonance frequency. The presence of a broadband spectrum will also make it difficult to stay away from resonance frequencies.

Theoretical studies have also been performed of the spread of the emission from the individual turbines to the grid. The concept of “transfer function” has been extended to the new concept of “overall transfer function”, linking the emission from one individual turbine with the total emission from a park consisting of many turbines into the grid. Simulations have shown that resonance frequencies, due to the cable network or due to capacitor banks, can result in large amplification of the emission.

Major international co-operations

The project team is working together with a major manufacturer of wind-power installations, with offices in Spain and England, concerning the spread of emission from the turbines to the grid.

Concrete use of results

The derived method for quantifying the impact of harmonic emission on the grid has been applied already for studying the impact of the emission from energy saving lamps in cooperation with Philips Lighting. The results of that cooperation are used directly in IEC standard setting groups.

The results concerning interharmonics are used to start a discussion on the need to change planning levels for interharmonics and non-characteristic harmonics.

Publications

K. Yang, M. Bollen, M. Wahlberg, Characteristic and non-characteristic harmonics from windparks, Int. Conf. Electricity Distribution (CIRED), Frankfurt, June 2011.

K. Yang, M.H.J. Bollen, M. Wahlberg, A comparison study of harmonic emission measurements in four windparks, IEEE Power Engineering Society General Meeting, Detroit, July 2011.

M.H.J. Bollen, S. Cundeva, S.K. Rönnberg, M. Wahlberg, K. Yang, L. Yao, A wind park emitting characteristic and non-characteristic harmonics, EPE-PEMC conference, Ohrid, Macedonia, September 2010.

K. Yang, M. Bollen L.Z. Yao, Theoretical emission study of windpark grids, Electric Power Quality, Utilization, Lisbon, October 2011.

Kai Yang, Math H.J. Bollen, Mats Wahlberg, Comparison of harmonic emissions at two nodes in a windpark, submitted to Int. Conf. on Harmonics and Quality of Power (ICHQP),Hong Kong, June 2012.

1.2.2 The impact of Wind Farms on Subsynchronous Resonance in Power Systems (V-309)

Since wind energy is one of the fastest growing renewable sources and thousands of MW are planned to be installed in Sweden, the impact of wind power units, particularly when clustered as large wind farms, on the dynamics of the power systems must be carefully investigated.

The aim of this project is to perform a preliminary study on the impact of wind farms on the risk of subsynchronous resonances in the power system when connected to series-compensated transmission lines. In particular, the focus of the project is on variable-speed wind turbines (full-power converter and doubly-fed induction generator, DFIG). As will be briefly discussed, variable-speed full-power-converter turbines seem to be immune to the phenomena, thanks to the decoupling between the generator and the transmission line offered by the back-to-back converter. The latter consideration also holds for wind farms connected to the power systems through HVDC systems, given a proper control of the HVDC system. Different considerations hold for the DFIG type. Through frequency scanning analysis, it will be shown that this type of wind turbines present a resonant condition at frequencies below the synchronous one. If a matching frequency exists in the transmission network due to the presence of the series capacitors, the system might become unstable and growing subsynchronous oscillations will be experienced. The resonant frequency of the DFIG is highly dependent on the converter (both the rotor-side and the grid-side converter) controller parameters as well as on the operating conditions. This dependency leads to a fairly wide range of frequencies, meaning that resonance can occur for a wide range of series compensation levels.

1.2.3 Assessment of the dynamic impact of large wind parks on the power system stability (V-311)

The project studies the concept of how (increased) damping can be achieved with wind power plants equipped with doubly fed induction machines. A traditional PSS can be obtained to damp oscillations normally seen in the power system.

The aim of this study is to examine how large scale wind power parks, distributed in a power system, affect the stability of the system, and whether the control of many wind turbines contributes to stability and damping.

The focus of the study is on wind turbines with doubly-fed induction generators (DFIG). These have been modelled to better reflect the general behaviour of DFIG turbines, and features have been added to the earlier used models. The interaction between DFIG wind power installations and power systems is different from the interaction between conventional, synchronous, generators and the power system. The impact of wind turbines is investigated through the use of linear and dynamic simulations. It has been demonstrated that DFIGs can be used for oscillation damping, and that they can improve the critical fault clearing time. However, different modes of oscillation appear in power systems where a significant proportion of the power is generated by wind power plants, and they may have an adverse impact on a power system after large voltage disturbances.

In order to examine the effect of wind parks on power system stability, models and control strategies are developed. Additionally a new method for controlling wind parks is presented, and a method for coordinating the control of multiple parks distributed throughout a power system is derived. These methods are used to demonstrate the effectiveness of wind parks in damping power system oscillations, and to compare the performance of wind parks and synchronous generators. A nonlinear signal, often used in power electronics based controllable components, has been used as a feedback signal to the wind park controller to create a POD function. A method using LMIs has been derived to simultaneously find a suitable POD coordination for multiple wind turbines so that a power system satisfies a specified damping ratio. The effect of DFIG POD controllers on power system damping has been compared to the signals normally used in PSS, and was shown to perform more effectively. A method for coordinating VSC-HVDC control and wind power production is also presented.

The impact of wind parks on power system has been investigated through the use of linear and dynamic simulations. It has been shown that even one wind park can make a contribution to power system damping. The performance of multiple wind parks with PODs has been compared to that of conventional synchronous generator power plants with PSSs in a large power system. It has been demonstrated that DFIG based wind parks can be used for damping oscillations. However, they may adversely affect on power systems after large voltage disturbances.

1.2.4 Problems in the power system related to wind power, An inventory (V-339)

Wind turbines are now installed in groups and parks, mainly at remote locations, far from strong transmission systems. This new way of producing electrical power introduces new challenges for all parties involved and experiences needs to be learned. In this report an inventory of problems related to connection of wind power to the power system has been performed. The inventory was done mainly by a questionnaire sent out by e-mail to representatives of network owners, wind turbine manufacturers, consultancy companies and wind turbine operators and owners. Although, most of the recipients expressed that this was an important project, few had the time needed to provide information. The goal of the project was to identify some problems that are interesting to investigate further in future projects. This has been satisfactorily achieved, despite of the poor response and that most of the received answers can be classified as administrative problems leading to electrical problems.

Four suggestions of problems that should be investigated are identified:

1. detecting islanding system,
2. zero sequence voltage and VSC (2 studies in this area)
3. system earthing, harmonics and inter-harmonics problems, and
4. resonance problems in the system.

The problems reported that lead to these suggestions are described in the report. Beside suggestions on studies that should be made, some general advices that relate to the connection of wind power have been documented. Some examples are:

1. The importance of relay protection coordination, judging from the answers poor relay protection coordination has resulted in many unnecessary wind turbine trips.
2. Fault recording facilities are recommended at every larger wind power installation.
3. Network owners should follow up on their technical requirements and grid codes to ensure that they are reasonable.

1.2.5 Perspectives on Power Electronics and Grid Solutions for Offshore Wind farms (V-340)

The report discusses principles on how to collect the power from individual offshore wind mills and then transmit the power to the onshore power system. Pros and cons for AC and DC systems are discussed regarding robustness and costs. Different principles such as nominal frequency, variable frequency or high frequency of an AC collecting grid are discussed.

From the summary:

The purpose of this study is to evaluate power electronic technologies for offshore transmission systems connecting offshore wind farms with the onshore high voltage AC grid. Special emphasis has been put on evaluating suggested technologies for high voltage DC transmission systems, which are anticipated to perform particularly well when the distance between the offshore wind farms and the strong connection points in the onshore network increases. Implementation of the European plans of massive investments in offshore wind power generation would impose exceptionally high stress on the existing high voltage AC grid. Ideas to create an offshore SuperGrid have been suggested by several associations, but the costs for such a grid are overwhelming and the technical challenges are substantial. Apart from the transmission system as such, related topics such as collection grids, are also briefly discussed.

In order to investigate the items mentioned above, a thorough literature study has been performed. Scientific journals and conferences as well as information on the web have been compiled. Scientific conferences have been visited, and a number of interviews (of which three have been reported explicitly) have been performed. The outcome of these studies has been put in relation to the research performed by the authors. Based on the findings of the studies, the following main conclusions could be drawn.

Presently offshore wind power only constitutes a few percent of the total number of wind power installations. Offshore projects therefore to a large degree inherit the onshore wind power technology. Accordingly wind farms located close to shore will utilize AC cables to transfer the power to the mainland if the transmission distance is sufficiently short. When the offshore wind farms move further out in the sea, the AC cable power transmission system must be replaced. Since long time, High Voltage Direct Current (HVDC) transmission has been looked upon as the natural, and perhaps only, viable alternative. Several approaches, backed by different manufacturers, to implement such HVDC systems have existed in the past, but it appears to the authors that lately the opinions of the different manufacturers have converged towards a common fundamental principle. The approach is based on voltage source converters using a new multilevel technology with cascaded bridges. It has gained a great interest from both industry and academia. The reason for the great attention is that output voltage waveforms of exceptionally high quality can be combined with converter efficiencies well above 99%. At least two manufacturers have shown that they are capable of offering this technology, which is an evidence of the potential for the technology. It is very likely that the great offshore projects that are currently planned will make use of this technology. In 2013 the two first hubs for offshore wind power generation should be in operation. These hubs could be the first nodes of an offshore HVDC SuperGrid based on multilevel converters with cascaded bridges.

1.2.6 Power Quality in the 130 kV connection point of a 110 MW wind farm (V-354)

Differences in power quality magnitude requirements are observed between different countries and between different power companies in Sweden. In Germany the requirements for harmonics and inter-harmonics up to 2 kHz are completed with requirements also for HF distortion up to 9 kHz for all system voltage levels. In Sweden there is no requirement above 2 kHz. It would serve all parties if the requirements could be harmonised and written in a way that clearly specifies how to measure and how to calculate different power quality magnitude values.

As the present converter technology for larger wind turbines (1 to 7 MW) normally works with a switching frequency in the range 2.5 to 5 kHz, it seems to be of interest to investigate if it is necessary to also include parts of the HF region in the measurements and in the requirements.

In Germany the power quality requirements depends on system voltage level and short circuit power in the connection point. This seems not to be the case in Sweden, at least not for harmonics. This difference needs to be further investigated.

Measurement transducers used in power plants normally have a limited bandwidth of 1-2 kHz. In order to investigate the HF region other transducers need to be used. In a similar way the measurement instruments need to have sampling frequencies that supports the HF transducers.

Svenska Kraftnät has a requirement on Fault Ride Through (FRT). To be able to investigate if the wind farm copes with this requirement one measurement system, in the present project, trigs on transient events, such as short circuits, and reports the events to the office.

The measurements are used to investigate whether the requirements stated by E.ON Elnät are fulfilled by the wind farm or not.

Goals: The project aims to investigate and find answers to the following issues.

- Is it required to measure HF distortion, above 2 kHz, in the sub-transmission system? How does the distortion depend on system voltage level and short circuit power?
- Is it possible to propose harmonised rules and requirements, on a general level, in the subtransmission connection point? How should the fact that the measurements are performed in only one connection point be treated? One goal with this part is to support network owners with power quality requirements. Another goal is that wind farm owners and manufacturers should face the same or similar requirements, independently of network owners.
- Are the requirements stated by Svenska Kraftnät and E.ON Elnät possible to measure and to fulfil?
- Is it possible to propose more distinct and detailed measurement procedures for each of the power quality magnitude? The aim is to be able to measure the wind farm contribution to the specific magnitude in the connection point. The parameters to be evaluated are harmonics, inter-harmonics, HF distortion above 2 kHz, flicker, resonances, unbalance and power system transients including FRT requirement compliance.
- What are the requirements on the measurement system? Differences between the systems used?

The project was started in March 2011 with a reference group meeting.

The Yokogawa instrument and the communication system were purchased and installed in late May 2011 in the switchyard measurement cabinet. The trig conditions were selected and activated.

During the first half-year of measurements the following results have been obtained:

- *FRT compliance:* Only two to three short circuits have occurred during this half-year measurement period. The wind farm power production was very low at these occasions so no clear statement can be given concerning the FRT compliance up to now. All measurement instruments (Yokogawa DL 850, Elspec G4430 and Elspec G4500) registered similar transient results.
- *130 kV disturbance recording:* E.ON Elnät updates the disturbance event list each month.
- *Harmonics/Inter-harmonics/HF distortion:* The standard IEC 61400-21 and the referred standards IEC 61000-4-7 and IEC 61000-4-30 state that the measurement shall be performed with consecutive 200 ms periods in 10 minutes intervals during one week. The FFT (Fast Fourier Transform) will then give values in a frequency spectrum for each 5 Hz. The sampling frequency shall be at least 20 kHz, which will generate a 10 kHz frequency spectrum.
    - *Yokogawa instrument:* Sampling frequencies between 20 kHz and 1 MHz have been used. The HF transducers for voltage and current connected to this instrument have bandwidths of around 300 kHz. The measurement period has varied between 200 ms (with 1 MHz) to 100 seconds (with 20 kHz). The voltage values above 2 kHz are very low. The current values above 2.5 kHz are very low.
    - *Elspec instruments:* The sampling frequency is set to 6 kHz for the Elspec G4500 connected to HF current transducers. Similar results up to 2.5 kHz are obtained as with the Yokogawa instrument. The low sampling frequency does not admit to analyse HF distortion above 3 kHz. The Elspec G4430 is connected to conventional transducers. The low bandwidth of these transducers does not admit to analyse HF distortion and maybe not even up to 2 kHz.
    - *Compliance with E.ON Elnät requirements:* For the short measurement periods all current harmonics requirements up to 2.5 kHz stated by E.ON Elnät are fulfilled. After conversion of measured current inter-harmonics to voltage values it was shown that also these requirements, stated in voltage, were fulfilled. So far no attempts have been done to measure during 10 minutes and 1 week. First the reference group, next meeting on January 19:th, has to decide on the required sampling frequency. If 6 kHz is enough then the Elspec G4500 measurement can be used.

- *Flicker*: The Elspec measurements and analysis of flicker show higher values than allowed. Yokogawa does not support any flicker evaluation. Elspec use the voltage measurements for the flicker evaluation. As for inter-harmonics this method is not possible for the estimation of the contribution from the wind power farm. It is required to start from the current measurements. The relevant frequency range for flicker is 0 to 20 Hz. A FFT spectrum in this frequency range for a 100 seconds long Yokogawa current measurement at 20 kHz showed very low values. Calculations based on turbine flicker coefficients also showed lower flicker values than the stated limits. Chalmers has used a method where the measured current values are first converted to id, iq values and then entered into the flicker algorithm. This method is the preferred one and will be used.

Major international co-operation: As a part of the project Swedish Power Quality requirements will be compared with German ones. Of this reason DEWI has been contacted and material has been obtained from this source.

National co-operation: Apart from the already mentioned contact with Chalmers, information has also been given from the ongoing Vindforsk PhD project V-306. Co-operation concerning damping of HF distortion through cables and transformers before reaching the subtransmission voltage level is underway. This co-operation may lead to a common article.

Expected concrete use of the results:

- Improved understanding of whether HF distortion needs to be measured
- Harmonised subtransmission power quality requirements
- Detailed information on evaluation methods to find the wind farm contribution
- Recommendations concerning power quality measurement systems in the subtransmission system

Publications: None apart from the possible common article mentioned above.

1.2.7 Power system stability and grid code requirements relevant for large-scale wind power integration (V-369)

Sweden and other Nordic countries have ambitious renewable energy source (RES) integration target. This will represent a significant share of wind power in the future generation mix of Nordic countries.

From a power system point of view, total understanding of technical impacts of this new generation source on the existing power system is vital to ensure a secure and reliable operation of the power system. Generators employed in conventional power plants are synchronous machines with round rotors or salient pole rotors - the modeling, operation and control of which are well understood by power system professionals. In addition, there are also well published operational and control related system experiences involving these types of machines. New generation of wind turbine systems include synchronous or induction machines together with power electronic converters.

For DFIG-systems, their (synchronous or induction machines and power electronic converters) combined effect is experienced by a power system. On the other hand, for full-power based systems, only the presence of power electronic converters are mainly felt by a power system. In this aspect, from a power system stability point of view, transient responses of wind power plants are different from conventional power plants.

In a higher wind power penetration scenario, wind power plants will need to contribute to system voltage and frequency control support, which is quite obvious and logical. The Swedish Transmission System Operator SvK, together with other Nordic TSOs is in the process of publishing updated sets of grid codes for wind power plants.

However, this needs to be done in a systematic way through detailed system level studies. There is not so much system level published operational and control related experiences with large amount of wind power contributing to the voltage and frequency stability of large transmission networks. Because of these reasons, detailed full scale system stability studies, among others, are vital to be able to characterize the dynamic behavior of a power system that includes large amount of wind power plants contributing to system voltage magnitude and frequency control support. Such studies will identify how the possible shift in generation-mix scenario in coming years should be dealt with from a power system stability and planning point of view.

Overall purpose and goal of the project package: The purpose of this project package is to carry out system stability studies to be able to identify the possible impact of large scale wind power integration on angle, voltage and frequency stability of a power system. Moreover, another purpose is to recommend on possible approaches to manage the impact of large-scale wind power integration on the stability of a power system.

A goal is to recommend on how to analyze this shift in generation-mix scenario from a power system stability point of view for system planners using the industry standard simulation tool PSS/E. In this regard, a goal is to evaluate in systematic manner the correlations between the results and system characteristics so that the findings from this project can be generalized. An ambition is to utilize the know-how from this project to address the similar issues in the Nordic level.

The project was initiated in close cooperation with the network planning department of SvK. Later, Fingrid and Statnet, and thus all the major Nordic TSOs cooperated with the project.

This project package consists of three main sub-projects focusing the impact of wind power on the angular, frequency and voltage stability of a power system. They are:

I. The effect of reactive power and voltage control response characteristics of wind plants on damping of inter-area electromechanical oscillations and the system impact of inherent reactive power oscillations from large number of wind farms due to voltage control.

II. The utilization of 'synthetic inertia' from large number of wind farms and it's impact on existing speed governors and system performance.

III. Towards the development of a set of grid code requirements for wind farms: transient reactive power requirements.

A short description of each part of the project is given below.

Part-I:

Background: The voltage controller of a wind farm could be in the form of a PI controller. Among the power system stability phenomena, poorly damped inter-area oscillations in the range of 0.1 Hz to 0.8 Hz are a concern for a reliable operation of modern large interconnected power systems. Existing poorly damped oscillations in voltage magnitude and angle will be sensed by wind farm voltage/reactive power controllers and could be reflected on the output of the wind farm in the form of varying reactive power with phase angle shift determined by the wind farm controller characteristics. Such reactive power oscillations from wind farms – induced from the existing power system phenomena – may, in the worst case, degrade the damping of the existing inter-area electromechanical oscillations depending on the wind power penetration level.

Depending on the parameter settings, the wind farm controller output may exhibit oscillatory behavior at a certain frequency. In other words, the wind farm will inject oscillatory reactive power into the grid to be able to control the magnitude of the terminal voltage. The frequency and damping of reactive power oscillations will depend on the PI controller and on network characteristics. When several wind farms from different part of the system will try to control the magnitude of voltage at their grid connection points, the system will experience oscillatory reactive power injections which will lead to oscillatory voltages. Such oscillatory voltages will be sensed by voltage transducers of synchronous generators voltage regulator and will be reflected on the output of the generators. Reactive power swings resulting from wind farms voltage controllers may cause system problem which may lead to system separation.

Purpose and goal: Few concerns for a power system planner in this regard are:

1. Among the power system stability phenomena, poorly damped inter-area oscillations in the range of 0.1 Hz to 0.8 Hz are a concern for a reliable operation of modern large interconnected power systems. Will reactive power oscillations from wind farms voltage controllers adversely affect this stability phenomenon?
2. How the wind farms voltage controller parameters tuning guideline should look like?
3. Will it be necessary to review the parameter tuning of power system stabilizers (PSS) of existing synchronous generators in the presence of wind farms voltage controllers?

4. Whether voltage oscillations introduced from wind farms will propagate through the system and impact the rotor angle or small-signal stability of existing synchronous generators?

Answers to these questions will require insights into dynamic characteristics of a power system including large amount of wind power. Insights into the dynamic characteristics of a power system are usually not easily evident from time domain simulations. Small-signal stability analysis using linear techniques is ideally suited for analyzing dynamic systems like a power system. This type of study together with extensive time domain simulations will be used to address the above mentioned concerns.

A goal of this part of the project is to assist network planners in predicting what to expect in terms of power system voltage and angular stability point of view when the planned large amount of wind power plants will contribute to system voltage magnitude control in a significant manner. In addition, another goal is to provide useful input in setting guidelines for tuning wind farm voltage controller parameters and for reviewing parameter tuning of PSS of existing synchronous generators, if needed.

Obtained results: The existing Nordic32 grid has been updated with several generators in Norway and in Finland. The model now exhibits a low damped oscillation at around 0.35 Hz where generators in south Finland oscillates against south of Sweden and Norway. It is found that a wind farm in north of Finland will degrade the damping of the inter-area mode of oscillation when operating at voltage control mode. However, when the wind farm operates in a reactive power control mode, the damping of the inter-area mode is improved. The analysis will be extended with taking other planned wind farms into account. The fundamental difference between wind farm voltage controller and that of synchronous generators will be investigated. Based on these, wind farm voltage controller parameter tuning guideline will be proposed.

Part-II:

Background: The incoming wind power integration scenario into the existing power system may vary considerably. The incoming wind power may replace existing conventional generators which were contributing/not contributing to the primary frequency control, or the incoming wind power may be compensated by the normal load growth or will be exported via new interconnections with neighbouring countries. The impact of wind power integration on the system frequency control function will depend on the integration scenario.

One of the concerns is the reduced system inertia in the presence of large amount of wind power which will result in higher rate of change of frequency deviation and higher frequency nadir after a generation disconnection scenario. It may lead into a situation where system level countermeasures like loading shedding may be required to guarantee the system security under post-disturbance conditions. The cause for the reduced system inertia is due to the fact that power electronic interfaces in variable speed wind turbines will normally hide generators inertia from exposing to the rest of the system.

However the hidden inertia of converter interfaced wind turbine generators can be made available to the power system to some extent during system frequency excursions if the control of a modern variable speed wind turbine is modified. The rotational energy stored in the rotating turbine blades could be utilized to provide short-term extra active power support. The inertial response support provided by wind turbines is termed as 'synthetic inertia'. It could be used to improve the system frequency stability. It also should be noted that the wind turbine need a recovery time after the short-term extra active power support.

This 'unusual' frequency dependent dynamic response of generating plants has not been experienced by a power system before. It is important to evaluate the performance of the power system frequency controller in the presence of the 'synthetic inertia' support from wind turbines. Such a system level operational performance study is needed to verify that the system frequency profile remains within the design limit for a dimensioning contingency in the presence of significant wind power plants with 'synthetic inertia' contribution.

The frequency control function of the power system is solely/mainly carried out by conventional generators using speed governing systems, as of today. Any untraditional way of frequency control measure ('synthetic inertia' support from wind turbines), should thus be viewed from the perspective of the existing speed governing systems i.e., how the performance and stability of the existing speed governing systems will be affected by this type of support. This will also help identifying potential adjustment needed, if any, to improve the frequency governing system performance in the presence of 'synthetic inertia' support from wind turbines.

<u>Goal:</u> A goal of this part of the project is to analyze how large amount of wind power plants can contribute to system frequency control support in a limited basis and how their contribution can be managed through the 'synthetic inertia' support. Another goal is to provide usable input in setting guidelines for tuning wind farm 'synthetic inertia' controller parameters.

<u>Obtained results:</u> A one mass model of the modified Nordic32 grid has been developed where the speed governors permanent and temporary droops have been modified accordingly. This one mass model will be used for the purpose of analysis, for example, parameters sensitivity analysis of the 'synthetic inertia' controller. Wind turbine models available in PSSE has been used in the calculation (the PSSE models already include synthetic inertia control option with the possibility to change the gain and wash-out time constant of the controller). Remaining study will include a full scale simulation on the Nordic32 model. Based on this analysis, parameter tuning guideline for wind farm 'synthetic inertia' controller will be addressed.

Part-III:
<u>Background:</u> New generation system based on wind energy resource generally employ a combination of synchronous/induction machines and power electronic converters to produce and transport electrical energy into utility grid. These types of generation systems are significantly different from the conventional synchronous machines. Particularly, DFIG-based wind power system has power electronic converters connected between rotor and stator

of generator, raising the combined effect of generator and converter into the power system.

Network planners of utilities want to have proper understanding of transient behavior of these new types of generating machines to manage their effect on the network in a reliable way. In addition, to be able to set proper transient response requirements on wind farms in grid codes, full understanding of the transient behavior of various wind turbine generators is necessary.

<u>Project aims:</u> Part 3 mainly deals with transient reactive power stability behaviours of DFIG-based wind power systems (DFIGWPS). Its main purpose is to provide more clear-cut understanding of voltage recovery from voltage dips at the grid disturbance by achieving below aims.

- Investigating the state-of-the-art understanding on wind turbine transient responses, DFIG-based wind power system in particular, mainly relying on current published reports from reliable sources.
- Assisting network planners in predicting what to expect in terms of transient reactive power response of large-scale wind power plants and the associated problem in related to system voltage recovery after a fault clearing.
- Helping utilities in determining the requirements with regard to the transient responses from wind turbines in their grid codes.

Project Results from literature investigation:

1. Observations from transient reactive power stability survey

Important observations of transient reactive power requirement, which are obtained from the literature survey, are summarised as below.

- As the scale of wind power is increased and connected to main power systems, intermittent wind power is treated as conventional generator in terms of supporting transient reactive power supply. This would highly need some change of conventional power system operational practice.
- The technical discrepancy of supplying transient reactive power between conventional generator (by electrical parameters) and DFIG-based wind power (by converter technology) might cause some complications to maintain transient voltage stability.
- The replacement of conventional generator by DFIG-based wind turbine could change/affect the stability behaviours of conventional generator, eventually expanding to the alternation of system-wide transient stability.
- The robustness of specific location within power systems, which is generally represented by either SCC (short circuit capacity) or X/R ratio, would be considered as important factor to determine transient voltage stability. Some research achievements recommend the connectable capacity of wind power on the basis of SCC.
- The change of electrical parameters within generator, which might be expected during by ambient temperature, aging and internal fault, could affect the transient voltage stability.

- Converter system equipped with control functions is commonly featured to support/manage voltage requirement (specified as LVRT in grid code) through reactive power supply at POI in the most DFIG-based wind turbine systems.
- Control parameters used in converter system are studied as a method to enhance transient voltage stability at grid fault network conditions.

2. Observations from benchmark grid codes review

Important observations of grid code requirement from the transient reactive power requirement perspective are presented as below.

- Most of benchmark grid codes speculate the LVRT requirement, requiring very fast discrete step-up recovery after clearing fault. However due to the limitation of converter capability, it is expected that LVRT might not be feasible at certain level of wind power capacity.
- It is required that system voltage should be restored to the certain level of normal operation. Particularly, wind turbine is required to inject reactive current with limited ramping capability into grid for supporting voltage during disturbance in some grid codes. This means that wind turbine is required to control/regulate reactive power support depended on voltage condition at faulted location.
- According to comparative review of benchmark grid codes, Nordic grid code, which is specified in Nordic grid code, is regarded as very stringent after clearing fault for up to 0.5[sec], where wind plant must raise the voltage at grid connection by 180% of nominal voltage every second.

Project Results from simulation studies:

Some observations, which are obtained from the simulation studies of Nordic 32 system, are summarised as below.

- It is obvious that the reactive power control capability of DFIG-based wind power is benefit at certain level of wind power capacity integration. Unfortunately, it is difficult to mention how much capacity is advantageous to voltage stability of power system in the scoping of this study.
- However, as the scale of wind power capacity is increased, the reliance of converter technology of DFIG-based wind power for transient voltage stability behaviour would be very affected by integration size of wind capacity.
- It is observed that large-scale DFIG-based wind power integration usually tends to cause transient instability of reactive exchange at POI between conventional generators and wind power, resulting in voltage instability.
- Furthermore, it is also shown that (N-1) contingency would more deteriorate the transient voltage instability due to the worsening deficiency of reactive power balance at the faulted POI.
- The effectiveness studies of control parameters within electrical control of DFIG-based wind turbine show their limitation of enhancing transient

voltage stability by changing the size of control parameters. That is, it is expected that instead of converter technology enhancement, FACTs-based voltage control devices such as STATCOM and SVC are more effective to manage transient voltage instability.

Recommendations for Nordic grid code (not completed):

Based on benchmark grid code review and simulation studies, some essential new requirements are summarised for LVRT amendment of Nordic grid code as below.

- Regardless of voltage control support capability, it is highly required that reactive power support from large-scale DFIG-based wind power shall be carefully controlled/coordinated with rest of reactive power supply resources in restoring voltage after clearing fault.
- Regardless of recommendation of Nordic grid code, it is not specified how much reactive power is the acceptable reactive power with respect to active power production from wind power plants in current Swedish regime. Likewise to German and Spanish grid code, it would be needed to speculate the requirement of reactive power control in detail.

Major international cooperation within the project
A co-operation has been established with all major Nordic TSOs (SvK, Fingrid, Statnet) within this project. Professor Kjetil Uhlen from NTNU, Norway, has also cooperated with this project by sharing a simplified equivalent model of the Norwegian power grid.

Excepted concrete use of results
It is expected that the results from this project could be used to update the Nordic grid connection code for wind farms.

1.3 Planned outcome of the projects

The expected results from the seven projects reviewed in this report are shortly described in Table 2.

Project number	Project title	Planned concrete use of results of the project
V-306	Harmonic distortion and wind power installations	Design rules for large wind parks; design of harmonic filters with wind turbines; setting of limits for harmonic emission at higher frequencies; methods for presenting the results of harmonic measurements; planning levels for harmonic emission. The project will cover both low frequency harmonics (up to about 2 kHz) and high frequency harmonics (about 2 kHz and above).
V-309	The impact of Wind Farms on Subsynchronous Resonance in Power Systems	Guidelines on how to avoid SSR in power systems related to wind power installations
V-311	Assessment of the dynamic impact of large wind parks on the power system stability.	As a guideline, describing how DFIG based wind power installations can be utilized for small signal stability improvements in large scale power systems
V-339	Problems in the power system related to wind power, An inventory.	Some further investigations that need to be done. Suggested studies: How to avoid influence of zero-sequence voltages/currents from converters. How to detect island operation.
V-340	Perspectives on Power Electronics and Grid Solutions for Offshore Wind farms.	How to connect offshore wind farms to the onshore power system in a sensible way.
V-354	Power Quality in the 130 kV connection point of a 110 MW wind farm.	For harmonizing power quality magnitude, requirements, calculations, and measurements among different countries and grid companies.
V-369	Power system stability and grid code requirements relevant for large-scale wind power integration.	The results could be used to update the Nordic grid connection code for wind farms

Table 2 Expected results from Vindforsk projects within the sub-area, “Power quality and system stability”.

1.4 Comparison of the Vindforsk III projects with international research and trends

The research areas focused within the Vindforsk III projects, surveyed in the present report, fit corresponds very well with international wind power research, with respect to target areas, research goals, and results, appropriately adjusted to Swedish conditions.

The Vindforsk III reports studied are in general of high international standard.

It can also be concluded that with respect to "trends and development" in Chapter 2 and "future research needs" in Chapter 3, there is a lot of research work to be accomplished within the next coming years, both with respect to general wind power related phenomena and with respect to specific local (Swedish) conditions for wind power installations.

2 Trends and development

This chapter describes the state of the art in the research on power quality and system stability related to wind energy integration in power systems. New findings and problem areas are identified and described.

There is a general agreement that the transmission and distribution of electric energy will be based on AC power system principles and conditions for the foreseeable future. The synchronous operating AC system will for a long time be the backbone of electric power systems. The integration of internal as well as external HVDC links will continue, as transmission corridors within a synchronous system, as connections between asynchronous systems, and to bring distantly generated power (offshore) into the AC system. The point where customers and producers "meet" will still be the AC system. Therefore the AC system will continue to be the level where the compatibility conditions have to be set. With respect to standardization on power quality, as well as on compatibility conditions, the discussions on what is needed, what is producible, what are the costs and who should bear them, will continue.

The general trend in wind power integration is towards larger wind power units, and larger wind power groups, farms and clusters, more remote from electric power consumption areas, both offshore and onshore. The technology concerning embedded generation is more or less settled, however some issues related to island detection, voltage control, robustness with respect to disturbances, and frequency control, are still relevant.

Compliance with the appropriate grid code is a major concern for each wind power installation. A big problem is the variety of similar but different grid codes, issued by the TSOs. The relevance of the different grid code requirements, and their specific formulations, varies. There is a debate on grid code issues between TSOs and wind power actors. The parties have reached a better understanding for the situation of the other party, with respect to conditions and obligations. The debate about grid code compliance will for sure continue and there is a belief that we will get grid codes that are more harmonized between different TSOs (at least within Europe), more adjusted to the specific conditions at the location for the connection, and, in general, more cost-efficiency adequate.

There are a number of technology areas, related to the possibilities and conditions for further wind power development, such as multi-terminal HVDC based on VSC technology, HVDC cluster technology, and circuit breakers for HVDC. Breakthroughs in these areas will have a significant impact on the possibilities for large scale wind power integration as well as for AC system power quality and stability improvements.

Research and development within wind power can generally be divided into the following areas:

- Wind turbine efficiency and reliability over a wide range of wind speeds.
  - This area is mainly focused by the wind turbine manufacturers.

- General and efficient grid code compliance, e. g the fault-ride-through criteria, for different power systems and markets, which might differ considerably.
  - This area is a major concern for the turbine manufacturers, but also for TSOs and wind power installation integrators.
- Power system integration compatibility and ancillary services.
  - This is an area that recently has attracted more interest for wind power installations, which can provide various ancillary services such as frequency and voltage control.

2.1 Power quality - Trends, findings and problem areas

Research and development related to wind energy with respect to power quality and system stability are driven by the fact that wind energy is now becoming a significant part of the total electric power supply and therefore also other performance criteria, than just reliable megawatthour-infeed, are derived and evaluated. The general trend is to make the wind power generation less dependent on traditional generation and ancillary service. New functionality such as to improve power quality and system stability is more and more included in wind turbines, wind power plants, farms and clusters. The need for higher level control and coordination is emphasized.

In general power quality is a matter of compatibility between different components and systems operating together. For compatible operation any component or system must be able to withstand the electrical environment in which the component or system has to operate (immunity). Any system or component must not inject unacceptable disturbances into the electric system where it is operating (emission). Power quality can be divided into the following areas: voltage level, voltage fluctuations, voltage dips and short interruptions, short term overvoltages, harmonics, subharmonics, interharmonics, resonances, and voltage asymmetry.

2.1.1 Voltage level

There are different opinions among different parties (grid operators, wind energy producers, and wind turbine manufacturers) about to what extent the wind power should contribute to voltage control and reactive power support. There are basically two trends in research and development today; one is towards clear and well defined interfaces between grid responsibility and requirements on generation facilities, and the other one is focused towards solutions that are technically and economically optimized for the integrated system of wind power generation and traditional network facilities, such as tap-changers and shunt compensation. The first trend is driven by TSO:s, regulators, and other authorities, mainly by regulations that put requirements on generation units, with respect to voltage control and reactive power capability for reliable grid operation. The second trend is more complex and mainly driven by universities and research institutes, on behalf of the rest of the society. Development is needed on the issue of integrated voltage control. Similar approaches have been seen on coordinated voltage control in transmission systems, especially in France and Italy, and in distribution systems, e. g. in the Tomelilla area, Sweden.

2.1.2 Voltage fluctuations

Voltage fluctuations caused by modern, DFIG or FSC (full scale converter), wind power generation are normally small and harmless and do not cause any power quality problems. However the wind turbine grid converter in an FSC unit could be used to improve the power quality in an area with voltage fluctuation problems.

2.1.3 Voltage dips and short interruptions

Voltage dips (sags) are known as the power quality problem causing the most economical damages in the modern society. Reactive power input to the connected grid during short circuits and earthfaults supports the overall voltage level and reduces the voltage depression in the rest of the system during the fault. FSC based wind turbines are well suited for such support.

Wind turbines combined with batteries, with a capacity of e.g. 15 minutes of rated power, have been studied and discussed to enhance the utilization of the wind turbines and to be able to contribute to frequency control. Such batteries can also be utilized to support a local network supplied by the wind farm during short interruptions.

Since it would be extremely expensive to eliminate voltage dips with a duration of up to a few hundreds of milliseconds, electric power consumers, especially sensitive to voltage dips, have invested in their own short term energy storages, such as SMES (Super Magnetic Energy Storage) or flywheels. Wind power plants with battery storage could support in a similar way. Even longer voltage dips could be mitigated with such batteries. The batteries could preferably be installed in the customer facility or at another location in the network, since the wind power plant might not be the optimal location for batteries to mitigate voltage dips and short interruptions.

2.1.4 Short term overvoltages

Short term overvoltages appear at sudden loss of load, in combination with long low loaded lines and especially cable networks, and when there is a fault on any voltage controlling equipment. A suitable dimensioned converter in a wind turbine could very quickly reduce such overvoltages in the vicinity of its connection point. With a smart control, a severe local voltage problem could have higher priority than the active power generation, resulting in reduced active power generation and increased reactive power consumption, to reduce the overvoltage.

2.1.5 Harmonics, subharmonics, interharmonics and resonances

Traditional harmonics are very much related to classic thyristor based converter technology, and are normally filtered out. For modern transistor based VSC technology, low order harmonics are not an issue any more. However higher order harmonics and interharmonics might be a problem. Active filters might be a solution in certain cases.

Resonances with respect to wind power installations are always a matter of interoperability between the power plant and the grid. Care has to be taken, especially with series compensated networks.

2.1.6 Voltage asymmetry

Modern wind power turbines are capable of producing a very symmetrical voltage, and should during normal operation not cause any problems in this area. Normally the wind power plant is set to produce a symmetrical voltage in the grid connection point. In certain situations it might be more valuable to enhance the overall grid properties by using the wind power plant to ensure a symmetrical voltage in another place in the network, e.g. the point of common coupling.

2.1.7 Frequency quality

The power system fundamental frequency is normally not regarded as a power quality issue, mainly because the frequency excursions in a modern power system are so small that they do not affect any specific equipment connected to the power system. The frequency level is, however, used as an indicator of the balance between the actual load and the set active power generation.

2.2 System stability - Trends, findings and problem areas

There are basically three kinds of power system stability; frequency stability, angular stability, and voltage stability.

- Frequency stability
    - Short term - frequency stability
    - Long term – active power balance
- Angular stability
    - Static angular stability
    - Transient angular stability – first swing
    - Small signal stability - damping
- Voltage stability
    - Short term – Quasi steady-state conditions are not reached after a severe disturbance with loss of transmission capacity (time frame 0-10 seconds)
    - Long term – With or without an initiating system disturbance, the power system operational conditions are gradually sliding towards lower voltages and higher currents, due to lack of transmission capacity or reactive power resources, compared to the load level (time frame 10 seconds – hours)

The issue of spontaneous transition into island operation and fault clearance capability has to be emphasized when wind power plants are equipped with voltage and frequency control.

Presently large scale offshore wind power farms and clusters are not very hot around Sweden. However, in Southern part of the Baltic Sea and in the North Sea, there are great plans and activities pushing for large wind farms (in the range of 500 MW) forming clusters (in the range of 1000 MW) and even inter cluster connections. Such large installations require sophisticated control on different levels.

2.2.1 Short term - frequency stability

The frequency influence on the power system load, i.e. if the frequency in the system increases the power consumption also increases, and vice versa, ensures small signal stable operation in the vicinity of the power system nominal frequency.

Power system components, especially rotating machines and transformers, are designed for a certain frequency, which implies that the frequency must be kept within certain limits, e. g 47.5 – 52.5 Hz. However, as mentioned in the power quality section, the frequency level is used as an indicator of the balance between the actual load and the set active power generation, i. e. if the frequency is too low the active power generation setpoint has to be increased, in order to release the reserves that are utilized to ensure the balance, when the set active generation does not match the actual consumption.

The frequency control is split into two parts: the automatic frequency control reserve and the disturbance reserve.

The automatic frequency control reserve is the power that is reserved for keeping the frequency within a specified interval. In the Nordic system, this interval is 49.9-50.1 Hz. The strength (droop) of the reserve is expressed in MW/Hz. In the Nordic system it has long been that the droop, R, should be at least 6000 MW/Hz within the interval 49.9-50.1 Hz. This means that when the system has a frequency deviation of Δf [Hz], it has allocated $\Delta f \cdot R$ [MW] of power from the frequency control reserve. With increasing load and a change in production toward more distributed generation it has been questioned if the old value of 6000 MW/Hz still is valid. The size of the automatic frequency control reserve is governed by the size of the random load variations.

The disturbance reserve is dimensioned to be able to take care of the maximum loss of generation due to a single fault, adjusted for the load reduction due to the frequency decrease. Presently the largest units in the Nordel system are Oskarshamn 3 and Forsmark 3, rated 1500 MW. It might be challenging to maintain the disturbance reserve during windy low load conditions, when one of the largest units is synchronized at full load. By tradition the frequency control in the Nordic system is supplied by the hydro power plants.

To ensure the power system robustness against loss of generation the disturbance reserve must not be utilized for frequency control during normal operational conditions, i. e. the frequency must not fall below 49.9 Hz.

In low load situations with a surplus of wind energy, the frequency control functionality might be more valuable than the corresponding megawatthours that cannot be delivered. Longer term frequency control must be based on pitch control and waste of wind energy. In a hydro power plant in frequency control mode it is possible to save the power, which is not the case for a wind power plant.

2.2.2 Long term frequency stability – active power balance

Active power balance over longer time than an hour is normally not regarded as a "frequency stability" issue. However, as wind power is a stochastically varying energy source, large efforts have to be focused on short and medium term power balancing, as the amount of wind generated power increases in the power system. The issue of power balancing with respect to varying wind power generation is both a matter of backup power resources, e. g. hydro power, and a matter of transmission capacity.

2.2.3 Static angular stability

The static angular stability is only affected by the voltage levels in the sending end and in the receiving end, the power transmission and the impedance between the sending and the receiving end. Since wind power generation sometimes is located closer to the load areas than the traditional generation, the static angular stability is increased.

2.2.4 Transient angular stability – first swing

Since the transient angular stability for many power systems, especially systems with typically long transmission lines from one area to another area, for a long time was the dimensioning criterion for the power transmission limitation, this kind of stability is very much studied and well understood.

Wind power generation located to the receiving end of a transmission system can significantly contribute to transient angular stability, by fast voltage control (based on the grid converter voltage control capability) and synthetic (artificial) inertia (based on the wind turbine variable speed technology).

2.2.5 Small signal stability – damping

For damping of power oscillations have, so far, voltage control with PSS and SVC been dominating, although damping based on active power modulation has been proposed.

Variable speed, converter based, wind power technology offers both voltage based and active power based damping possibilities. The most obvious damping function is achieved by adding PSS functionality to the grid converter voltage control function. However, utilization of the quite large rotating inertia in the turbine by decreasing and increasing the speed, provides for more demanding damping applications.

2.2.6 Short term voltage instability

Short term voltage stability mitigation is quite demanding, both with respect to speed and with respect to power. The only reasonable method to counteract short term voltage instability is by load shedding, either event based or voltage based. For situations that are on the limit to go unstable voltage boosting by the wind power grid converter might be sufficient to bring the short term voltage instability issue into a long term voltage stability issue.

2.2.7 Long term voltage instability

Long term voltage instability mitigation is also demanding, in a similar way as short term voltage instability mitigation, however, the time to take actions is a bit longer. Although time is longer, the active power deficit in the problem area has to be compensated, either by increased local active power generation or by increased transmission capacity, e. g. by reactive power support. Active power reserves in wind power plants in consumption areas, to mitigate voltage instability is probably not realistic. However, the possibility of voltage boosting and reactive power support to increase the transmission capacity, at least temporarily, is a feature that could very well be utilized in converter based wind power plants in the load area, to gain time for other actions, such as gas turbine startup or selective load shedding, to become effective.

2.2.8 Islanded operation and fault clearance capability

There is a clear trend towards increased control capability of wind power installations in general. There is always a risk for power system disturbances ending up in system separation of such a kind that a balanced island is formed. With increased voltage as well as frequency control capability in wind power installations, the risk (or chance!) of successful transition to island operation increases. Island operation with other kinds of primary energy sources, such as hydro, gas or oil fired generation is quite common.

So far most grid companies are very clear in their opinion that islanded operation based on wind power is not accepted. All wind power installations have to be equipped with reliable island operation detection, normally based on detection of abnormal frequency or abnormal voltage. The main reason for not accepting islanded operation based on wind power is the uncertainty concerning fault clearance. It is also a matter of responsibility for the power quality in the island network.

In small power systems, where the total load and geographical extent is small compared to the wind power plant under consideration, the requirements on the control systems are a bit different, since all changes in load or generation are relatively larger. The control parameters for the voltage and frequency control have to be chosen differently. There is a trend towards increased utilization of wind power as the main source of generation in smaller systems.

A problem area is to reliably detect islanded operational conditions – to just check voltage level, frequency level and rate-of-change of frequency is probably not enough. Voltage phase angle comparison between the generation unit under consideration and a point in "the main system" might be a possible way to reliably detect islanded operation. Other systems could be based on active detection to check the power system short circuit capacity in the point of wind power connection.

Reliable fault detection methods and systems for power systems fed by converters with a very low short circuit capacity have to be derived. For smaller systems it might be easy, but for a traditional subtransmission or distribution system, where the protection schemes are based on distance, underimpedance and overcurrent protection, the challenges are considerable.

Imagine the Swedish power system, mainly fed from wind power installations, based on full scale converters, with a short circuit current of the same magnitude as the load current. – How to design a reliable fault clearing system, is a great challenge, which sooner or later has to be addressed.

2.3 Significant research and development projects

This section describes a number of selected research and development projects, as well as some sources of statistics and trend information within the wind power area, available on the Internet.

From the survey it is clear that, today, there is much more research activities related to large wind power installations, power system integration and power system stability than activities related to power quality.

2.3.1 European Wind Energy Association (EWEA) activities

The European Wind Energy Association (EWEA) is the voice of the wind industry, actively promoting the utilization of wind power in Europe and worldwide. EWEA coordinates international policy, communications, research and analysis. EWEA also organizes high-profile industry events.

Within the area of wind energy and grid interaction, EWEA is presently focused on the following subjects:

- Design and operation of the power system with large amounts of wind power
- Grid connection requirements for wind power plants
- Generation adequacy and security of supply

2.3.2 International Energy Agency (IEA) Wind activities

The International Energy Agency (IEA) Wind agreement is a vehicle for member countries to exchange information on the planning and execution of national large-scale wind system projects and to undertake co-operative research and development (R&D) projects called Tasks or Annexes. The following ongoing or completed tasks within IEA Wind are related to power quality or system stability:

- Power systems with large amounts of wind power
- Integration of wind and hydropower systems
- Offshore wind energy technology deployment

- Dynamic models of wind farms for power system studies

2.3.3 EU funded projects on wind energy

Wind energy is one of the most promising renewable energy technologies, and is an area in which there have already been many developments and improvements to make electricity generation more effective. Between 1995 and 2005, cumulative wind power capacity in the EU increased by an average of 32% per year. Developing wind resources offshore is a particular priority of the Community. Siting wind farms in an environmentally sensitive manner is important. Since 1998 the EU has funded more than 40 projects on wind energy with a total contribution of more than EUR 60 million since 2002.

These projects advanced knowledge in:

- Components and systems for turbines and farms
- Integration of wind power into the grid
- Wind resources forecasting
- Demonstration of large scale systems for onshore and offshore wind farms

Wind energy is one of the priorities of the current Framework Programme (FP7). Below selected EU funded research projects within FP6 and FP7 are presented.

MARINA PLATFORM - Marine Renewable Integrated Application Platform
Abstract: MARINA is a European project dedicated to bringing offshore renewable energy applications closer to the market by creating new infrastructures for both offshore wind and ocean energy converters. It addresses the need for creating a cost-efficient technology development basis to kick-start growth of the nascent European marine renewable energy industry in the deep offshore.

SAFEWIND - Multi-scale data assimilation, advanced wind modeling and forecasting with emphasis to extreme weather situations for a secure large-scale wind power integration
Abstract: The aim of this project is to substantially improve wind power predictability in challenging or extreme situations and at different temporal and spatial scales. Going beyond this, wind predictability is considered as a system design parameter linked to the resource assessment phase, where the aim is to take optimal decisions for the installation of a new wind farm.

7MW-WEC-BY-11 - Pilot Demonstration of Eleven 7MW-Class WEC at Estinnes in Belgium
Abstract: This action focuses on demonstrating the development of a cost-effective large scale high capacity wind park using new state-of-the-art multi megawatt turbines coupled with innovative technology used to stabilize the grid. A key objective of the '7-MW-WEC-by-11' project is to introduce a new power class of large-scale Wind Energy Converters, the 7MW WEC, onto the market. The new 7MW WEC will be designed and demonstrated at a large scale: eleven such WECs will be demonstrated in a 77 MW wind park close to Estinnes (Belgium).

EWIS - European Wind Integration Study
Abstract: The project aims to work with all the relevant stakeholders especially representatives of wind generation developers. The study will use results from detailed network and market models of the European transmission system for scenarios representing immediate and longer-term needs. The recommendations will be aimed at developing, where possible and appropriate, common European solutions to wind integration challenges.

WINDGRID - Wind on the Grid: An integrated approach
Abstract: Wind on the Grid is a project focused on preparation of the European electricity network for the large-scale integration of wind farms through the design, development and validation of new tools and devices for its planning, control and operation in a competitive market.

SUPWIND - Decision Support for Large Scale Integration of Wind Power
Abstract: The project has the following objectives: 1) Demonstrate the applicability of decision support tools based on stochastic analysis and programming for operational management of grids and power plants 2) Demonstrate the applicability of strategic analysis tools for decision support for long-term management of grids 3) Detailed analysis of improved coordination mechanisms between grid operators, power plant operators, power exchanges, etc.

NIGHT WIND - Grid Architecture for Wind Power Production with Energy Storage through load shifting in Refrigerated Warehouses
Abstract: The Night Wind project proposes to design grid architectures for Wind Power Production combined with Energy Storage means of load management of Refrigerated Warehouses (Cold Stores). Refrigerated Warehouses are constant power users, day and night.

DESIRE - Dissemination Strategy on Electricity Balancing for large Scale Integration of Renewable Energy
Abstract: DESIRE will disseminate practices which will integrate fluctuating renewable electricity supplies such as wind power into electricity systems using combined heat and power. This will allow for an increase in pan-European trade of electricity. It will also improve the economic competitiveness of both CHP and wind power, and allow the proportion of renewable electricity that can be absorbed by the system to increase.

HIPRWIND - High Power, high Reliability offshore wind technology
Abstract: The aim of the HiPRwind project is to develop and test new solutions for very large offshore wind turbines at an industrial scale. The project addresses critical issues such as extreme reliability, remote maintenance and grid integration with particular emphasis on floating wind turbines, where weight and size limitations of onshore designs can be overcome.

2.4 Significant demonstration projects

The European Commission is supporting and funding a number of demonstration projects related to power quality and system stability. Through the demonstration and deployment of innovative technologies, the EEPR (European Energy Programme for Recovery) OWE (Offshore Wind Energy) projects are forerunners in the sector. They contribute to the priority objectives of the European Wind Industrial Initiative, which have been set up in the frame of the EU's Strategic Energy Technologies plan. One of two areas for offshore activities is support to the development of module-based solutions for the grid integration of large amounts of wind electricity generation. Within this area a project providing an integrated inter-connection solution for the wind farms in the Kriegers Flak area in the Baltic sea (Germany, Denmark) is supported.

Below selected EU funded demonstration projects are summarized.

TOP WIND - Technology platform Operational Programme Wind
Objective: The European Wind Energy Technology Platform (TPWind), established in 2005, is today a well-established and broadly recognized network of approximately 150 wind energy experts, who play a key role in supporting the development of wind power in Europe. The main aim of the TOP Wind project will be to ensure the proper functioning of the European Wind Energy Technology Platform over the 2010 2013 period, as well as to increase its effectiveness, impact, visibility and network (especially by reinforcing existing relationships, and developing new ones, with oil & gas, ocean and grids operators, who can cooperate with wind energy players to reduce fragmentation of EU R&D activities).

TWENTIES - Transmission system operation with large penetration of Wind and other renewable Electricity sources in Networks by means of innovative Tools and Integrated Energy Solutions
Objective: A group of 6 Transmission System Operators (Belgium, Denmark, France, Germany, The Netherlands, and Spain) with 2 generator companies, 5 manufacturers and research organizations, propose 6 demonstration projects to remove, in 3 years, several barriers which prevent the electric system from welcoming more wind electricity, and wind electricity from contributing more to the electric system. The full scale demonstrations aim at proving the benefits of novel technologies (most of them available from manufacturers) coupled with innovative system management approaches. The contribution of wind energy to the system will show how aggregated wind farms can provide system services (voltage and frequency control) in Spain. The aggregation of wind farms with flexible generation and loads will be demonstrated in Denmark. Increasing the flexibility of transmission networks will be tested in Belgium (existing sensors and coordinated power flow control devices avoiding possible large scale instabilities induced by wind farms in the CWE region) and in Spain (dynamic wind power evacuation capacity using real-time computations based on short-term generation forecasts and use of a mobile Overload Line Controller). Off-shore wind farms are addressed from a security viewpoint. Secure HVDC meshed networks will be validated in France using simulations and full scale experiments of two different HVDC circuit breaker technologies. Off-shore wind farm shut downs under stormy conditions will be demonstrated in Denmark using the world largest off-shore wind farm with balancing power provided by the Norwegian hydro capacities through an HVDC link. The experimental results will be integrated into European impact analyses to show the scalability of the solutions: routes for replication will be provided with benefits for the pan European transmission network and the European electricity market as soon as 2014, in line with the SET plan objectives.

7MW-WEC-BY-11 - Pilot Demonstration of Eleven 7MW-Class WEC at Estinnes in Belgium (2007)
Objective: This action focuses on demonstrating the development of a cost-effective large scale high capacity wind park using new state-of-the-art multi megawatt turbines coupled with innovative technology used to stabilize the grid. A key objective of the 7-MW-WEC-by-11 project is to introduce a new power class of large-scale Wind Energy Converters, the 7MW WEC, onto the market which has the potential to significantly contribute to higher market penetration levels for wind electricity in Europe. The new 7MW WEC will be designed and demonstrated at a large scale: eleven such WECs will be demonstrated in a 77 MW wind park close to Estinnes (Belgium). The wind park will be the first large-scale on-shore wind park in Belgium and the first in the world that will consist of this mega turbine power class. Key challenges related to wind power will be addressed in this demonstration action ranging from technical issues (network stability and security), to financial aspects (cost effectiveness) to environmental issues (landscape pollution). First, the mega turbines will be developed and installed in series; this is envisioned to significantly reduce costs and increase the market value. Second, new power electronics technology and improved wind forecasting will be used to stabilize the grid in the high capacity wind park. Improved forecasting is envisioned to furthermore improve the cost-effectiveness of the high capacity wind park (reduced imbalance costs, improved commercial value). Third, the 7MW turbines will be used to maximize wind energy capacity, while reducing landscape pollution and environmental impact: such a WEC generates more than double the energy in the same given area when compared to conventional 2MW turbines and requires the placement of fewer turbines when compared to conventionally used wind turbines. Lessons learned in developing the high capacity Estinnes wind park will be adapted to a different national context with a weak grid system, Cyprus.

TOPFARM - Next generation design tool for optimisation of wind farm topology and operation (2006)
Objective: An increasing part of the turbines to be installed in the future are foreseen to be sited in large wind farms. Establishment of large wind farms requires enormous investments putting greater emphasis on optimal topology design and control. Today, the design of a wind farm is based on an optimization of the power output only, whereas the load aspect is treated only in a rudimentary manner, in the sense that the wind turbines are required only to comply with the design codes.

2.5 Wind energy information sources

There are a large number of information sources on wind power activities available on the Internet.

2.5.1 Global Wind Energy Council (GWEC)

GWEC is a trade association working to create a better political environment for wind energy, working on legislative, regulatory affairs, financial systems and public relations. GWEC also publishes a lot of information on statistics and global trends. There is huge and growing global demand for emissions-free wind power, which can be installed quickly, virtually everywhere in the world.

2.5.2 American Wind Energy Association (AWEA)

The AWEA website strives to provide information on all facets of the wind industry, from small wind for individuals to large wind farm development. AEWA is among other items addressing "Utilities and Wind Power", "Transmission and Wind Power", and "Wind Integration and Reliability".

2.5.3 Wind Energy – The Facts

Wind Energy - The Facts (WindFacts) was a European project for Competitiveness and Innovation that ran from November 2007 to October 2009. The 'Wind Energy – The Facts' publication is considered to be one of the most important wind energy reference in the world. It presents a detailed overview of the wind energy sector, with the most up-to-date and in-depth information on the essential issues concerning wind power today. The latest edition (March 2009) of the 'Wind Energy - The Facts' publication includes chapters on Grid integration.

2.6 Major research groups

There are a large amount of universities and other research groups around the world active in the wind power area. In this section a number of selected research groups, and their activities, focused on the issue of power quality or system stability are shortly described.

Aalborg University, Denmark
The university has a dedicated research group of wind turbine, which is quite focused on the wind turbine itself. However the Department of Energy Technology is quite active in the power quality area related to wind power.

The University of New South Wales – Sydney – Canberra – Australia
The School of Electrical Engineering and Telecommunications is driving a number of projects in the areas of "Power quality – harmonics and transients" and "Wind power integration".

Technical University of Denmark, including Ørsted Institute (now also including Risø)
DTU has extensive research activities in all areas related to wind power technology and power system implementation, including power quality and system stability.

Chalmers University of Technology, Sweden
Chalmers University is very active in the electrical parts of wind power research and development, including power quality and power system stability.

Technical University of Catalonia, Spain
The Technical University of Catalonia in Spain is active in the area of wind power technology, with a number of ongoing research projects

Technical University of Lisbon, Portugal

The Technical University of Lisbon is active in a number of wind power related areas, including power quality and system stability.

Royal University of Technology (KTH) in Stockholm, Sweden
Also at KTH a quite extensive amount of wind power related activities are going on.

Delft University of Technology, the Netherlands
Even though the Delft University of Technology research activities are focused on rotor aerodynamics and wind turbine design, a lot of activities are directed towards power quality and system stability

Eindhoven University of Technology, the Netherlands
Energy is one of the strategic areas at Eindhoven University of Technology. Both power quality and system stability issues are addressed.

China Electric Power Research Institute, China
CEPRI is extremely big, with extensive laboratory resources as well as simulation facilities. Renewable energy (wind power) is addressed as one of many research topics.

The University of The West Indies, at St. Augustine, Trinidad and Tobago
This university is active in the area of power quality in small power systems supplied by a significant amount of wind power.

Queen's University Belfast
Queen's University is much more active in system stability issues related to system stability than to power quality.

University of Illinois, USA
Power system stability both with respect to wind farm modeling and with respect to wind turbine modeling and aggregation are studied at the University of Illinois.

University of Calgary.
Energy storage to improve power quality from wind power has been studied at the University of Calgary, as well as power system stability aspects of wind power integration.

Xian Jiaotong University, China
It is believed that many of the Chinese universities and research centers are very active in the different disciplines of wind power integration, such as power quality and system stability. However, their web sites are not always very informative.

Glasgow University, United Kingdom
Glasgow University has published a number of papers related to wind power and power quality or system stability.

University Duisburg-Essen, Germany
Throughout the years, a number of papers have been published related to wind power and power quality or system stability.

VTT Technical Research Centre of Finland
The research centre is active in all aspects of wind power integration.

SINTEF and NTNU, Norway

SINTEF and NTNU are active in all aspects of onshore and offshore wind power.

Fraunhofer-Institite for Wind Energy and Energy System Technology, Germany
The institute addresses all aspects of wind power technology and interaction.

University College, Dublin, Ireland
Papers on increased wind power penetration with respect to power quality and system stability are published.

ECN, the Netherlands
ECN is active in wind power development and focusing on transfer of technology to the market.

Manchester University, United Kingdom
Connection-to-shore technology for large offshore wind farms, and all related aspects, are studied.

Utility Wind Integration Group, USA
The group activities are focused on accelerating the integration of wind generation into utility power systems.

National Renewable Energy Laboratory, USA
Among other things the laboratory aims at eliminating barriers to large-scale deployment

The following universities also show some activities in the wind power area:
Helsinki University of Technology
University of Dortmund, Germany
The University of Aberdeen, United Kingdom
National Wind Technology Center, Colorado, US

Organisations like **ENTSO-E** and **NERC** are very important, although they do not take part in wind power integration research activities. However, they set the scene for the grid requirements and conditions for compliance with wind power installations.

3 Future research needs

Trends, findings and problem areas related to wind power integration and power quality or system stability, are identified in the previous section. These areas are also the main targets for future research needs. Issues related to

- the increased size of wind installations,
- increased contributions to the total electricity generation from wind power,
- grid code development and harmonization,
- wind power generation control and ancillary services, and
- fault clearance in wind power dominated systems,

will be focused for the near future research efforts.

As renewable energy sources, mainly wind power, is becoming a significant part of the total generation of electric power, these renewable sources also have to participate in the power system stability, control and balance with respect angle (inertia), frequency (active power) and voltage (reactive power), for short term (fractions of a second) as well as for longer term (hours and maybe days).

With respect to power quality, focus has so far been on emission from wind power installations. Less attention has been paid to the actual needs for power quality of different aspects in the power system. Issues like how to find the most cost effective compatibility levels for different aspects of power quality in different parts of the power system, and how to achieve these levels, will probably be focused. It has to be emphasized that modern converter controlled wind power installations might improve the power quality in the vicinity of the grid connection point.

In the following subsections some specific topics for near future research are presented.

3.1 Energy market design and principles for ancillary services

Today, energy is traded on market based principles. Automatic and manual frequency control is an oligopoly with the TSO as the only buyer within a specific area. With a different design of frequency control, disturbance reserve and energy market there might be new incitements to make owners of plants powered by renewable energy sources willing to offer ancillary services instead of just energy.

This might also lead to cases where the boundaries between the systems (production, distribution and transmission) need to be softened, in order to obtain an efficient and cost effective system.

3.2 Production and load randomness and predictability

Classic generation is predictable to a larger extent than renewable generation. A number of issues and questions arise with respect to generation and load balancing and prediction, for short term and for longer term, with a considerable amount of wind power in the system:

- How random is the production from a larger area (country) with renewable production [1, 2]?
- How is the system influenced by randomly varying production? How does random production influence the requirements on transmission capacity and amount of automatic frequency control?
- Is it possible to make the production/consumption less random than today? Will the power system in some way benefit for a change in randomness of production/consumption compared with today. What are the driving costs to minimize variations?
- Can loads be used for frequency/balance control instead of production? What are the possible pros and cons of using loads for control?

3.3 Grounding principles

Grounding and connection principles to reduce the number of faults related to renewable energy sources, is a subject for further research. According to one of the reports, (V-339), there is a difference between different countries that might depend on how the power plant handles different grounding principles. A closer investigation of how grounding principles interact with converters and protective relays and affect the reliability of the existing grid, would be of interest, as well as a study on the interaction between power systems with different grounding principles.

3.4 Artificial/Synthetic inertia

Artificial/synthetic inertia can be used to improve the spinning reserve of a system. Artificial inertia is not used today. Artificial inertia can also reduce possible problems related to random production (in short time-scale). Would it be a good idea to introduce artificial inertia and what size should it have? Parts of this might be covered in project V-369.

3.5 Harmonic levels

The acceptable harmonic level in the grid is fixed by the grid owner in order not to interfere with other equipment. Are these levels at present unnecessarily hard? What can be gained by reducing these requirements? Will different wind power plants then disturb each other or other equipment, both production and consumption? Present projects seem to focus on the harmonics from a wind farm. The harmonics are also dependent on the surrounding grid. Further research needs to be carried out to find how the surrounding grid affects the harmonics from a wind power plant.

3.6 Combination smart grids/smart production

Smart grids aim at minimizing the influence of varying production, whereas smart production tends to minimize certain system specifics such as losses depending on customer actions. It must be assured that these two mechanisms not interfere with each-other. An interesting research area would thus be the combination of smart grids and smart production. Smart production could then include an energy storage intended for a longer time (hours).

3.7 Fault handling

Fault ride-through is a word used today indicating that the wind power plant should not be disconnected from the grid during faults in the connecting grid. But is must also be studied how a wind power plant, with its limited fault current, affects the existing protection system. Which faults can be detected and which cannot, with traditional fault detection principles. What should be done when there is a fault in the grid? Will the requirements on fault handling lead to new/different principles and investments in for example communications?

4 Project references

This section is a summary of current and previous published results of the authors of the seven reports, within the field where they asked for funding by Elforsk/Vindforsk.

4.1 V-306

Math Bollen has a long history of publications within power quality. During the last years he has published the following results within wind power.

[3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]

The result for harmonics during the last 10 years is:

[14, 15, 16, 17, 3, 18, 19, 20, 4, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 6, 5, 13]

Whereas the intersection between harmonics and wind power is somewhat smaller, which indicates that this field has not been very well studied yet.

[3, 4, 6, 5, 13]

4.2 V-309

This is a rapport that describes a phenomenon. The report in itself describes what and why things happened but research related articles are not expected from this project. The authors are well known within the subject of wind power and sub-synchronous resonance.

4.3 V-311

This project was given to Mehrdad Ghandhari, KTH but the main contributions seem to be from Katherine Elkington, KTH (PhD student). Mehrdad is a co-author of all the published material within the project (except the dissertation).

[36, 37, 38, 39, 40, 41, 42, 43]

4.4 V-339

This is a survey rapport and no other publications than this report is to be expected.

4.5 V-340

This is a survey rapport and no other publications than this report is to be expected. There are no publications directly related to the subject or to the authors. However, both authors are well known in their area of expertise.

4.6 V-354

Apart from the contact with Chalmers, information has also been given from the ongoing Vindforsk PhD project V-306. Co-operation concerning damping of HF distortion through cables and transformers before reaching the subtransmission voltage level is underway. This co-operation may lead to a common article.

4.7 V-369

N. R. Ullah has a solid background in handling of wind power/renewable power. His research activities has among other things dealt with artificial/synthetic inertia, the influence of grid codes on system stability/individual plants and how wind farms can be integrated in the power system.

[44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62]

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