Aspects of Wind Turbines and CHP in a Liberalised Swedish Power System

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ASPECTS OF WIND TURBINES AND CHP IN A LIBERALISED SWEDISH POWER SYSTEM

PH.D.-THESIS

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Preface

This thesis is part of the demands for fulfilling the PhD-program at The Technical University of Denmark. The studies carried out have been conducted at Ørsted-DTU, Section of Electric Power Engineering and Malmö University, Department of Technology and Society. The project has been financed by Sydkraft Research Foundation – I am very thankful for the support from Sydkraft; without the financial support from the Sydkraft Research Foundation this project could not have been conducted.

The thesis is organized in a relatively short »main thesis« with the most important studies and results, and with a rather large number of appendices that contain studies that are not necessarily »key issue« but still related to the thesis topic. There is no »right« or »wrong« ways of reading this thesis. If the reader is not particularly related to the operation of electric power systems, it is recommended to read the appendices A, B, C and F before reading the main thesis to get acquainted with the terminology and the basic problems related to power system operation. When starting to read the theses just read along – and refer to the appendices when ever interested or when referred to in the thesis.

The direct referring to references in the text is sparse. This is to ease up the reading, but also due to the fact that the references are used among each other, and the thesis is generally a result of the general impression of the references.

It can be argued that some of the findings of the thesis refer to an industry paradigm that applied some years ago. This is to some extend true, given that the development has been very rapid the last years, both when it comes to wind turbine and CHP integration, industry development of the electric power industry and technology of e.g.. wind turbine concepts. However, at the time the study was inaugurated, the work carried out, the scope of the project and the investigations to be done were considered both novel and relevant to study. Since that time, much of the projections made in the assumptions of the study have become a reality: The Barsebäck power plant has been closed down, discussions about a massive introduction of wind power in Sweden in the magnitude of ~10 TWh/year with an installed base of 4000 MW across Sweden has been ongoing, a massive introduction of ~3500 MW installed base of wind turbines in Southern Sweden alone have been-turned into actual plans, the Swedish ISO Svenska Kraftnät has introduced ARISTO in their analysis of the impact of wind power in Sweden has accentuated the need for a wind turbine model, that can be used with ARISTO, as well as the terms for connecting wind turbines to the electric power system in Sweden (among others) has been extended with detailed demands for reactive power compensation, that were not present at the time the study was commenced. The thesis should be read and interpreted knowing this fact, and acknowledging that at the time of the study, these were not facts as they are today.

There are many people to thank for help and support during the project. As might known, the conditions for conducting this project have not been optimal, as one of the project primus motors died during the first part of the project. The decease of Prof. Jan Rønne-Hansen almost threatened to »tumble« the project to the ground – but thanks to the extraordinary effort of both my supervisors Bo Eliasson , Arne Hejde Nielsen, Peter Falster and Sture Lindahl and the members of the reference group Ola Carlson, Olof Samuelsson, Poul Sørensen, Jacob Østergaard, John Eli Nielsen and Martin Randrup. Without the help and support from you, and without the constructive discussions over my subject I have had with you, I would not have been able to complete this study. Thank you a lot.

I am thankful as well to all my colleagues and the staff at both Ørsted-DTU and Malmö University for being friendly and helpful. A special thank must go to Lars Lindgren at Malmö University for his endless work with me in the simulator room, where he helped me with all kinds of trouble with my simulations – and for just being there during the endless summers spent at Östra Varvagatan 11H in Malmö with me when no one else were at the university.

Looking back on the project, I cannot imagine how I would ever have completed this study without the love, help and support from my beloved girlfriend, Sandie. It is incredible to think back on how you must have suffered when I came home in the evenings depressed and bragging about everything and nothing. I cannot express how thankful I am every day that I am with you.

Kgs. Lyngby, January 2005 Kim Johnsen

Abstract

As wind turbines and other kinds of embedded generation are introduced in larger and larger quantities in power systems, it becomes more and more vital to be able to perform power system studies with these kinds of generation. This PhD-project focuses on investigating the impact of wind turbines and CHP being integrated in the southern Swedish electric power system, from a »worst-case« perspective. Corollary, the thesis points out potential levers for coping with the identified problems in a liberalized electric power market along both the technical and commercial dimensions

The thesis presents a model for simulating wind farms in real-time, using ARISTO (Advanced Real-time Interactive Simulator for Training and Operation) as simulation system. For this use, an aggregate wind farm model for use in real-time power system studies is presented in this paper. MATLAB/Simulink is used to model the wind farm, to operate with the ARISTO simulator system. The choice of ARISTO was a prerequisite for the study. Using the MATLAB/Simulink-environment in model development features high adaptability and makes it possible to model what ever is needed. The wind farm model presented here is based on the aggregate wind farm principle, on basis of the so-called “Danish concept” for wind turbines. Having only “Danish concept” wind turbines in-scope was a deliberate choice during the project, as (1) these wind turbines still represent a significant part of installed capacity and new installments, and (2) as other wind turbine concepts, such as wind turbines with doubly fed generators, were assessed to still having too severe development needs to come about before becoming the preferred choice, even though they are commercially available today

This model is used to investigate large scale integration of wind turbines and a combination of wind turbines and CHP in the Swedish electric power system. The simulations are made using the real-time simulation tool ARISTO, and regard a case where wind farms or wind farms and CHP in combination have been introduced in the southern part of Sweden to replace the nuclear power plant, Barsebäck. The simulations indicate that under both stable and faulty operations two problems are worth noticing: Problems with maintaining a stable voltage level and the latent risk that a wind farm could trigger power oscillations. Multiple case study simulations show that the Southern

Swedish electric power system could suffer from voltage collapse caused by the introduced wind turbines and CHP. Furthermore, an analysis of the power spectrum densities of the wind farms shows that there are power oscillations within the range of oscillations that may trigger modes in the Nordic electric power system.

To encounter the problems that are identified in the case study, the introduction of means to control the reactive power flow is needed, which can be done using conventional technical means. When it comes to facing the potential threat of wind turbines trigging power system oscillations, this problem can be encountered by proper wind turbine design.

It is suggested that to ensure that these means are actually taken, an increased focus on commercial actors to take part in balancing the reactive power production and consumption in a liberalized market. Liberalizing the delivery of reactive power will give consumers incitements to reduce their impact with respect to reactive power consumption to a minimum, as well as ensure that the demanded production capacity will be available in the long run. The impact of introducing a liberalized market for reactive power has been seen to be significant in India. In the case of wind turbines, this will give incitement for the wind turbine owner to reduce the reactive power consumption, which again will invoke a demand for wind turbines with less impact on the electric power system with respect to reactive power.

Resumé (abstract in Danish)

Det bliver mere og mere vitalt at være i stand til at gennemføre studier af elforsyningssystemer når der introduceres større og større mængder af vindmøller og andre decentrale elproduktionsenheder. Dette ph.d.-projekt fokuserer på at undersøge den påvirkning, som vindmøller og decentrale kraft-varmeværker har på det sydsvenske elforsyningssystem, set udfra et ”worst-case” perspektiv. Ydermere påpeger projektet på mulige tiltag, der kan være medvirkende til at løse i de identificerede problemer, som en sådan introduktion af vindmøller og decentral kraft-varme kan have i et liberaliseret elforsyningssystem, set både ud fra tekniske og kommercielle synsvinkler.

I afhandlingen præsenteres en model til brug for simulering af vindmølleparker til brug med ARISTO (Advanced Real-time Interactive Simulator for Training and Operation) som simuleringsværktøj. Modellen er udviklet på basis af ”aggregate wind farm”-princippet, og kan benyttes til realtidsstudier af elforsyningssystemer. MATLAB/Simulink er benyttet til at modellere vindmølleparken i, og modellen interagerer herigennem med ARISTO. Valget af ARISTO som simuleringsværktøj var en forudsætning for studiet. Brugen af MATLAB/Simulink giver en fleksibilitet i modelleringen, som giver mulighed for tilpasning og mulighed for at ændre modellen efter behov. Den modellerede vindmøllepark er baseret på ”Danish concept” vindmøller. Valget af netop denne vindmølleteknologi beror på (1) at disse vindmøller stadig her bredt anvendt i dagens elforsyning, og (2) da nye vindmølleteknologier, såsom vindmøller med doubly-fed generatorer, stadig blev vurderet til at være på et teknologisk stade, hvor der var store udviklingsbehov, til trods for at disse teknologier er til rådighed teknologisk.

Denne vindmølleparkmodel er anvendt til at undersøge interaktionen ved en stor-skala implementering af vindmøller og en kombination vindmøller og decentral kraft-varme i det sydsvenske elforsyningssystem. Simuleringerne er udført i realtid med ARISTO-simuleringsværktøjet, og undersøgelserne er struktureret omkring en case hvor vindmølleparker eller vindmølleparker og decentral kraft-varme i kombination erstatter det sydsvenske kernekraftværk Barsebäck. Simuleringerne indikerer at der både under stabile driftsforhold og under forhold hvor der opstår fejl i elforsyningssystemet er især to problemstillinger, der er værd at tage i betragtning: Problemer med at opretholde spændingsstabilitet, og latente risici for at der opstår effektpendlinger i nettet. Flere af

simuleringsstudierne viser at det sydsvenske elforsyningssystem kan risikere spændingskollaps forårsaget af de introducerede vindmøller og decentrale kraft-varme værker. Ydermere viser en analyse af den producerede, pulserende aktive effekts frekvensindhold at vindmøllerne forårsager effektpendlinger i de frekvensområder, som kan anslå udæmpede modes i det nordiske elforsyningssystem.

For at imødegå de identificerede problemer er introduktion af metoder til at opretholde reaktiv effektbalance en nødvendighed, hvilket kan gennemføres på konventionel teknisk vis. Når det kommer til risikoen for effektpendlinger anslået af vindmøller kan disse problemer imødegås ved at stille krav til vindmøllernes mekaniske udførelse.

Det anbefales i afhandlingen at man, for at sikre at disse behov opfyldes i et liberaliseret elforsyningssystem, at man øger fokus på de kommercielle aktørers incitament til at tage del i balanceringen af reaktiv effekt, både når det kommer til produktion og forbrug af reaktiv effekt. Liberalisering af leverancen af reaktiv effekt vil give forbrugere incitament til at reducere deres reaktive effektforbrug, ligesom det på lang sigt vil være med til at sikre at den nødvendige produktionskapacitet er tilstede, idet der vil opstå et incitament til at producere reaktiv effekt. De positive effekter af at introducere et reaktivt effektmarked har vist sig at være store i bl.a. Indien. Når det kommer til vindmøller, så vil dette give incitament til at ejere og producenter af vindmøller vil arbejde for at udvikle vindmøller med mindre indvirken på den reaktive effektbalance, hvilket igen vil være med til at stabilisere driftsforholdende når det kommer til opretholdelse af spændingsstabilitet.

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1.INTRODUCTION

1.1.Background

The political demand for renewable energy resources during the last twenty years has made it possible to industrialize e.g. the wind power utilization. The turn-over in application of the embedded generation, such as wind turbines or combined heat and power plants (CHPs) is significant, especially in Northern Europe. The installed capacity will also most likely increase in the coming years, also in Sweden. The politically decided energy proposal by the Swedish parliament indicates a significant increase of installed wind power in the years to come. Today there are plans to build wind farms with an installed capacity of several hundred MW's. This kind of embedded production will naturally have a strong impact on the existing electric power system as well as the coordination of the daily operation of the electric power system and other electricity production facilities.

This project concerns the introduction of embedded generation in the electric power system transmission and distribution and analyses the impact of embedded generation on the electric power system, in particular when large amounts of non-dispatchable power production is connected, as well as develop means of coping with the negative side effects of embedded generation on the electric power system

Much focus is on power quality, especially the voltage quality, as well as the demand for maximum utilization of the existing electric power system. This has become a major concern due to competitive reasons.

1.2.Purpose of the thesis – project focus and scope

This PhD-project focuses on investigating the impact of integrating wind turbines and CHP in the southern Swedish electric power system, from a »worst-case« perspective. At the time of initiating the study, no prior studies of a large-scale integration of wind turbines and CHP in southern

Sweden following a close-down of vast amounts of the nuclear power production, which was the political aspiration at the time of initiating the study. The aim of this study is to represent a perspective of what issues to be aware of from a »worst-case« perspective, if such a massive shift from nuclear power to wind turbines and CHP's is conducted. Furthermore, the thesis points out potential levers for coping with the identified problems in liberalized electric power market along both the technical and commercial dimensions[1]

The project will firstly focus on the operation of the existing electric power system when a large amount of embedded generation has been installed. Among the disturbances, specifically voltage fluctuations and voltage instability is analyzed. Concerning voltage instability the application of induction machines as generators in e.g. wind farms gives rise to concern since the reactive power balance depends heavily on the instantaneous power production. These studies are performed in the real-time system ARISTO (Advanced Real-time Interactive Simulator for Training and Operation), which is briefly presented in Appendix J, and for that purpose it is needed to develop a model for real-time simulation of wind farms.

Secondly, the project will focus on aspects of the integration with respect to the liberalization of the electric power business, and discuss what is needed to ensure that the needed capacity for e.g. compensation and power quality attainment is present. To fully understand the behavior and problems in liberalized markets, they have to be studied independently, which is done in Appendix D (on quality features of electric power) and Appendix E (liberalization aspect related to electric power systems). To include these more commercial and market dynamic aspects is important in evaluating means of coping with the identified problems from the simulation studies. It is the clear belief that having levers for coping with the identified problems that reach beyond the »pure« technical levers is important when evaluating the impact of a large scale integration of wind turbines and CHP's in a liberalized power market, as the evaluation of how to come about problems in a liberalized market is based on both commercial and technical aspects. Furthermore, it is a governing belief from this study that designing the market correctly would commercially drive much of the needed technical

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[1] When regarding the conclusions in this thesis, it is important to keep the historical context of the research work in mind. The research was carried out in the period 2001 to 2004, and at the time of commencing the work the approach and the topics were novel. However, development within this field is rapid, and thus some of the conclusions may retrospectively seem less novel at the time this work is presented.

investments timely from a simple commercial value-creation perspective, which eliminates much of the political discussion (and the resulting delay and down-grading of technical investments needed) that would appear, if the same technical means were to be forced through from regulatory hands. This governing belief can and will of course be challenged by highly technical oriented readers of this thesis, that may argue that proper coping of electric power system issues is a technical discipline, not a commercial discipline. This argument cannot be countered with one »silver-bullet«-argument – but it is of course interesting to regard the decision taking processes across most industries as of now: Firstly, how often demands from regulatory authorities in tightly regulated industries results in a political response and resulting delay of the needed technical investments, and secondly how often commercial arguments have much more importance than pure technical arguments. In both cases, the technical improvements are taken »hostage«, often because those having the technical insight down-grade the importance of communicating the commercial aspects of a technical improvement. Going forward, bringing forward the impact potential of technical improvements from a commercial value-creation perspective will become increasingly important, especially in a liberalized electric power industry. Thus, there is a clear link between how to develop the characteristics of the liberalized power market and coping with the identified technical problems of a large scale integration of wind turbines – a link that is likely to become increasingly important going forward.

The choice of ARISTO is a prerequisite for the study[2]. Never the less, ARISTO with its graphical interface and real-time capabilities features new opportunities for investigating the dynamics of a power system adapting a top-down approach using visualization of the dynamic behavior and thereby seeing things as they happen rather than the classical bottom-up approach used in power system investigation, identifying and analyzing isolated issues through »number-crunching« of simulation calculation outputs. A description of ARISTO and the concept is given in Appendix J.

The scope of this study's investigation of wind turbine concepts is narrowed to wind turbines if the so-called "Danish concept", i.e. technology for wind turbines based on an asynchronous generator being directly connected to the grid through a transformer. As it appears from the literature in

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[2] The rationale for this prerequisite is twofold – firstly, a detailed model of the Sydkraft model was available in ARISTO (thus, the use of ARISTO would save modeling time during the project), secondly the project should show that ARISTO can be applied in research projects.

the references and in the appendices, new turbine concepts have been studied. The issue of choice of turbine technology has been thoroughly discussed during the progress of the study. The rationale for narrowing the scope to the “Danish concept” only falls into four main reasons:

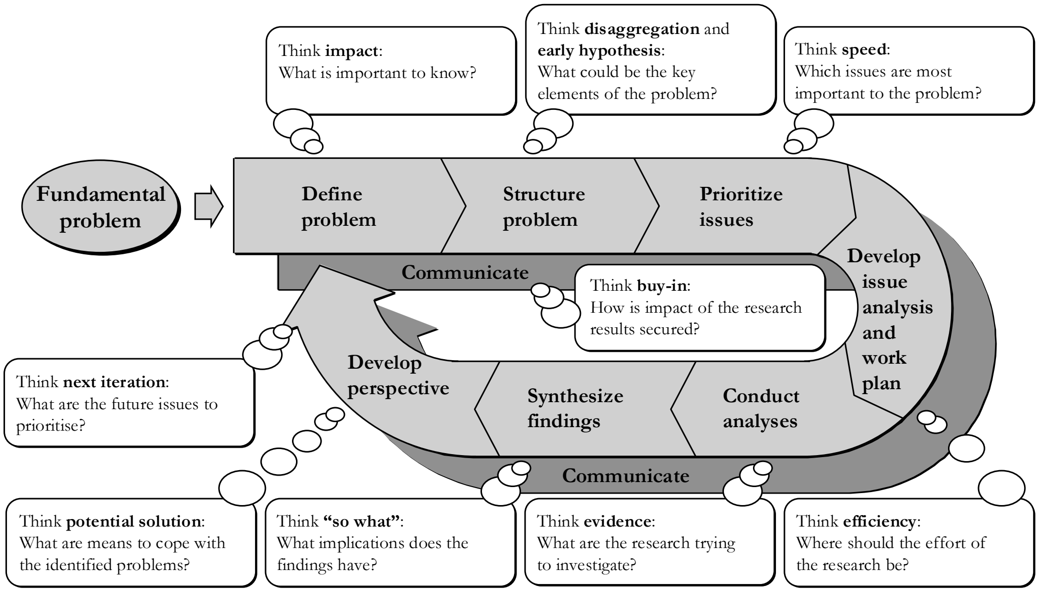
- At the time of launching the study, this technology was still a significant solution, that was not considered obsolete in any way.
- The intention of the studies is to represent a “worst case” when it comes to voltage stability, as this was identified as the main issue – thus, the Danish concept wind turbine with its load dependent reactive power consumption must be considered to be the one with the most significant impact compared to other technologies. This has also been the approach in other studies.
- Though commercially available, wind turbine concepts based on e.g. doubly-fed generators have not yet proved to be commercially viable at the time of the study. Even though one of two large off-shore wind farms in Denmark has been installed using wind turbines with doubly-fed generators. It could be argued that that this wind farm (Horns reef in Jutland, Denmark) erected using doubly-fed generator concept is a »multi-billion dollar monument« proving that the technology is not “there yet”, with significant downtime due to equipment breakdown. Furthermore, the larger of the two and the most recently build (Nysted wind farm south of Sealand, Denmark) is equipped with a technology which is very close to the original Danish concept.
- The performance of wind turbines designed with e.g. doubly-generators or converters is highly dependent on the properties of the settings of the control parameters of converters and other power electronic devices in the machine. These data are hard to retrieve, and during the study it has not been possible to access this kind of data, not even in a sanitized version. On this behalf, it has been decided to go for a concept, for which data is just somewhat retrievable

Going forward, new wind turbine concepts will of course come about, and accentuate widening the scope of studies like this to include other wind turbine concepts. However, at the time of the study, it was the strong hypothesis that this »turn-around« for the “Danish concept” was not in the short-term future.

1.3. Project problem solving approach

This study is, as opposed to many other power system studies, very top-down driven[3]. The rationale for taking the top down approach is that this project concerns the impact of wind farms and CHP on the Swedish power system as a whole, and the issues that are deep-dived into are the ones considered most important from this overall perspective rather than a pre-defined prerequisite set of properties to be investigated. The concept of this problems solving approach is illustrated in Fig. 1.

Top-down research approach with issue-driven problem solving



4

Fig. 1. Principles of top-down research with issue-driven problem solving approach. As opposed to traditional bottom-up research with a topic-driven problem-solving approach, the top-down research deliberately focuses on (1) creating the big picture, and (2) addressing issues with the highest impact potential.

The problem solving method used in this project can best be described as issue-driven. Issue-driven problem solving, where the effort is focused on issues with the highest impact potential

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[3] Hence, ARISTO comes as the natural choice of simulator.

rather than what may be of theoretical interest to investigate in order to ensure »sweeping all the corners«, is believed to create the more present value of the research.

Driving research with this approach reduces the need to conduct a classical “state-of-the-art” literature study in order to identify the issues to address in the study, as the issues are identified through an initial analysis of the big picture. Spending effort on uncovering “state-of-the-art” within an entire discipline does not feed in to the creation of results (and value) in a top-driven approach, as only the most prominent issues will be prioritized going forward. Within each of these prioritized issues, building of knowledge through literature studies will of course be needed, as the research progresses, but the top-down approach ensures that the literature study is closely linked to the issues that it serves to clarify.

Hence, focus is aimed at »sweeping« the most important parts of the »floor«, that can be seen, giving a perception of a larger area of »cleaner floor« rather than ensuring that all »corners« are swept, regardless of whether or not the effort actually increases the perceived »level of cleansing«.

2. BASIC BEHAVIOUR OF EMBEDDED GENERATION

2.1.Wind turbines

2.1.1. Wind behavior

The presence of wind is basically caused by the fact that the Earth is exposed to different amounts of solar energy dependent on the location, and this generates large convection currents in the atmosphere. [69]Furthermore, the rotation of the Earth and the inertia of the air causes a relative displacement between them, resulting in wind. In the lower parts of the atmosphere, where most man-made structures (including wind turbines and wind farms) are placed, these large convection currents of air are retarded by friction against the earth as well as obstructions by large objects, such as mountains, woods or buildings, and this retardation forces the currents to change direction, and hereby the winds become turbulent and fluctuating. As these turbulences are very complicated to describe it is generally accepted to consider the winds fluctuations as stochastic with some kind of seasonal trends. Also when it comes to short term descriptions (i.e. on timeframes of up to minutes or hours), is it generally accepted to consider the wind as stochastically fluctuating.

The representation of how the wind behaves is usually described by its velocity field, $\boldsymbol{v(x,y,z;t)}$, that again often is expressed linearly as a sum of a mean value of the wind in the certain position, $\boldsymbol{V_0(x,y,z)}$, and a stochastic residual, $\boldsymbol{\varepsilon(x,y,z;t)}$, i.e.[20]

$$v(x,y,z;t) = V_0(x,y,z) + \varepsilon(x,y,z;t) \qquad (1)$$

The stochastic residual is the component that describes the variations in the wind, and is distributed with a mean of 0 and a variance of σ_ε^2, given as

$$\sigma_{\varepsilon}^{2} = \frac{1}{\tau}\int_{t=0}^{t=\tau}\left(v(x,y,z;t) - V_{0}(x,y,z;t)\right)^{2} dt \qquad (2)$$

that can be regarded as a measure of how large the wind fluctuations are. Here the value τ indicates the period of time observed.

2.1.2. Fundamental principles for wind turbines

The basic principle of wind turbines is to convert the kinetic energy of the wind into electric energy. Usually this is done in an aerodynamic system that basically uses the wind to drive rotating blades to first transform the kinetic energy of the wind into a torque on a rotor shaft of a wind turbine, which is directly coupled to a generator where the torque on the shaft is used for generating electric power. (This chapter in general refers to the references [20], [69], [72] and [5], among others)

One common design is a design using a vertically erected structure (tower) on top of which is an adjustable house (nacelle), that has the generator and mechanical transmission, and to which the wind turbine blade rotor and its shaft, is mounted, as shown in Fig. 2. Often, the wind turbine blade rotor is equipped with two or three blades[4] which rotates around a horizontal axis, and has an asynchronous machine[5] as a generator. Eventually, there is some build-in compensation of the asynchronous machine, often just a static reactive compensation of the magnetization consumption of reactive power[6] to improve the voltage stability of the surrounding electric power system

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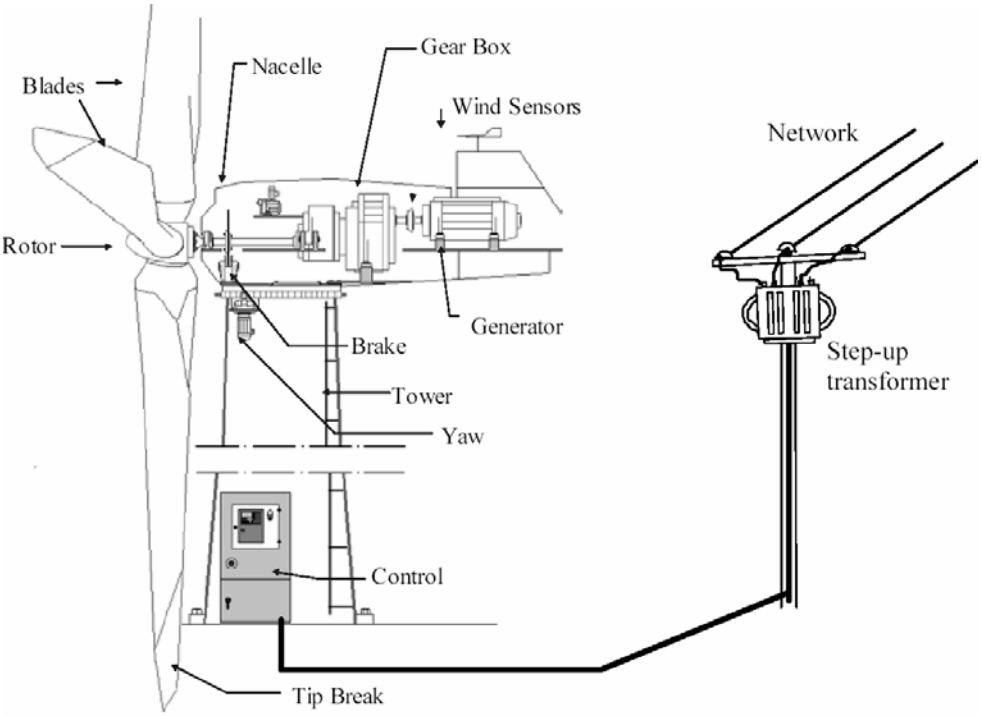
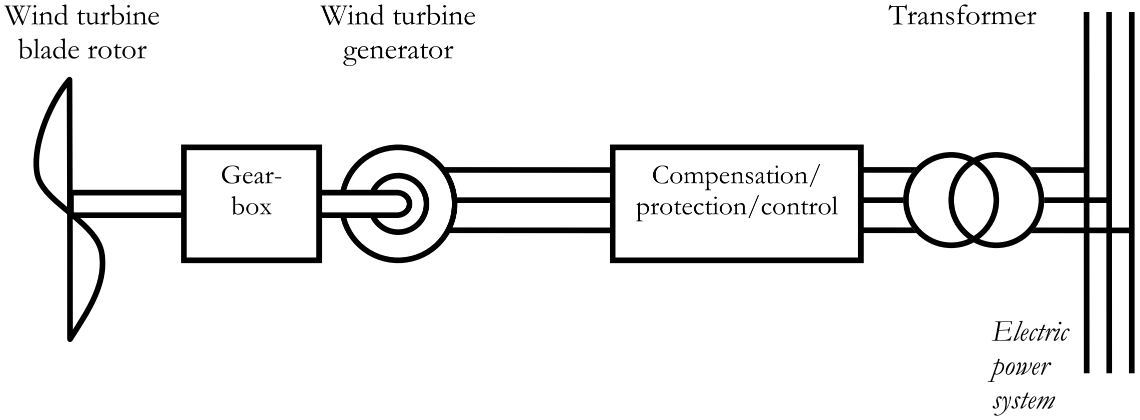
[4] Most frequently, two or three blades are used, as they are cheaper than using more blades. Using two blades is even cheaper than using three, but if used, the blade rotor must rotate at a higher angular speed, in order to extract the maximum of the wind power. This demands special material features of the rotor blades for two-bladed designs, as they have to be both lighter and stiffer. This is why the three bladed rotor is most frequently seen. Application of either a two or a three bladed rotor technology relies on a total design survey; there is no generally preferred technology

[5] Asynchronous generators are often used as they are the cheaper alternative and demand less maintenance. Other kinds of wind turbines exists, such as doubly fed asynchronous generators, conventional synchronous machines or synchronous machines with permanent magnets .Though the application of asynchronous machines as generators lead to complications to the surrounding electric power system, the other available technologies are not widely used mainly due to the installation costs (to the manufacturer/owner of the wind turbine) and their maintenance.

[6] Sometimes, some kind of dynamic reactive compensation gear, e.g. static VAr compensators, is also installed; this is often seen where more wind turbines are clustered in larger wind farms.



(a)



(b)

Fig. 2. General design of a wind turbine; (a) wind turbine, consisting of a blade rotor which is connected through a gearbox to a generator , which converts the mechanical power to electric power, which is again connected to the electric power system, to which the generated electric power is supplied[72], (b) schematic representation of the general design of a wind turbine.

The output power from such a system, i.e. a single wind turbine, can usually be described by

$$P_W = \frac{1}{2} \cdot \rho \cdot A \cdot C_P \cdot v^3$$

where $\boldsymbol{v}$ is less than a maximum wind speed for the distinct wind turbine, ρ is the density of the air, $\boldsymbol{A}$ is the total area that the wind turbine blades cover during a full rotation, $\boldsymbol{C_P}$ is the so called power efficiency factor of the wind turbine (i.e. a measure of the efficiency with which the wind turbine converts the kinetic energy in the air into electric energy) and $\boldsymbol{v}$ is the velocity of the air, which relies on various matters, e.g. the turbulence, time of the year and other parameters, in a somewhat stochastically manner, as briefly discussed in section 2.1.1.

The air density, ρ, is dependent on the meteorological state of the atmosphere, i.e. on temperature, humidity, and air pressure, that vary in time and place depending on the actual situation, but if the timeframe is limited to a small period of time, it is reasonable to consider this parameter as more or less constant.

The power efficiency factor of the wind turbine, $\boldsymbol{C_p}$, is a parameter that for each level of production of power in the wind turbine is given as a feature for each and every independent wind turbine. It can be interpreted as a sort of efficiency factor, which measures how much of the energy present in the wind is converted to electrical, active power by the wind turbine. For any specific kind of wind turbine, a certain characteristic for the values of $\boldsymbol{C_p}$, dependent on the active power production, is usually provided by the manufacturer. An example of such data is given graphically below, in Fig. 3.

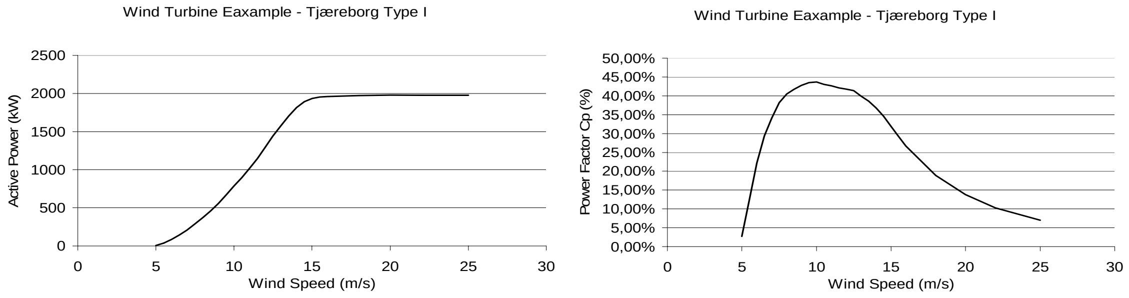


Fig. 3. Example of production characteristics for a wind turbine; (left) wind to electric power characteristic, showing the production level for a single wind turbine at a certain wind speed, (right) Cp-characteristic, showing the dependency of Cp of the wind speed.(The data reprinted here is for the "Tjæreborg I"-wind turbine, that is a test turbine made by Elsamprojekt A/S, Denmark, deployed in Jutland, Denmark. It is equipped with an induction generator that has a nominal generator power of 2000 kW).

From the characteristics in Fig. 3 it can be seen that the power production levels out when the wind speed reaches a certain level; this is due to the regulation of the wind turbine. The reason why such regulation is done is that it makes the operation of the wind turbine easier, as the wind power production is consequently fairly constant under these circumstances.

2.1.2.1. Wind turbine concepts

Many kinds of wind turbines, featuring different methods of converting wind power into electric power have been developed. In general, the basic principal concepts of wind power conversion can be categorized into two main categories: fixed speed wind turbine systems and variable speed turbine systems.

2.1.3. Fixed speed wind turbines

The simplest wind turbine concept is the fixed speed turbine system, where the wind turbine generator is directly electrically connected to the electric power system. Basically, the over-all concept features a rotor which is mechanically coupled to the rotor shaft of the wind turbine generator which is then directly connected to the electric power system, as shown in Fig. 4.

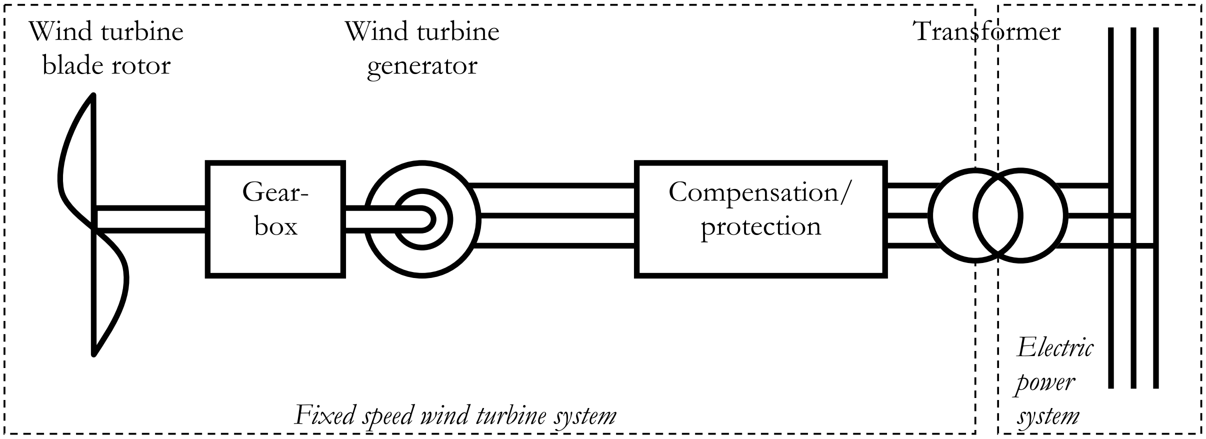


Fig. 4. Fixed speed wind turbine system concept; the wind turbine blade rotor provides mechanical power (as a mechanical torque) through a mechanical gear box system to a wind turbine generator rotor shaft. The wind turbine generator converts the mechanical power to electric power, and the generator then supplies the electric power to an electric power system, to which it is directly connected, through a transformer (eventually some protection and/or compensation gear, e.g. short-circuit protection, soft starter gear and static capacitor banks).

Usually the wind turbine generator featured in fixed speed wind turbine is either a traditional asynchronous generator (the most common) or a synchronous generator. As the generator is directly connected to the electric power system, the system frequency of the electric power system also becomes the system frequency of the wind turbine generator and hence the system frequency of the full wind turbine system. Principally, the wind turbine rotor blade will always rotate at the same speed independent of the wind turbine[7], and the gear box is designed to make the blade rotor rotate at a speed, that gives an optimal conversion from wind power to electric power.

As said, the most commonly used generator is the standard asynchronous generator. Using an asynchronous generator in a fixed speed generator wind turbine system results in a durable and cheap design both when it comes to investment costs, maintenance and operations. However, using an asynchronous machine as a generator demands the availability of a relatively strong electric power system, with a reasonable short-circuit level, to supply the asynchronous generator with the necessary excitement of the rotor. The fact that the asynchronous generator is not externally excited,

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[7] Some fixed speed wind turbine systems feature a more complicated mechanical gear box, that makes it possible to make the wind turbine blade rotor to rotate at 2 or more different distinct speeds. A fixed speed wind turbine system with a gear box, which makes it possible to operate at different mechanical rotational speeds on the blade rotor makes it possible to better adapt the wind power extraction from blowing wind to electric power. This effect can also be obtained by having e.g. two generators in the system or a generator with two winding systems.

but gets its rotor excitation from the electric power system to which it is connected causes a lack of control over the reactive power flow of the generator; and as the asynchronous machine draws out excitation current from the electric power system, it consumes reactive power when connected, whether it operates as a generator, a motor or unloaded. Applied as a generator, the reactive power consumption of an asynchronous generator is tightly coupled to the active power production, and varies (as such) with the rate of production, making the compensation of the reactive power consumption to a dynamic problem and not just a static problem that can fully be compensated by passive capacitor banks. Thus, the appliance of asynchronous generators in fixed speed wind turbine systems results in a latent voltage stability problem, caused by the reactive power consumption, which severity relies on the properties of the electric power system and on the concentration of wind turbines. When it comes to the active power, the dynamic behavior of the wind invokes a dynamic behavior of the active power produced from a wind turbine. Even though the asynchronous generator can reduce the mechanical dynamics of a wind turbine[8], the dynamics in the active electric power output (and the resulting reactive power consumption) of the wind turbine cannot be considered insignificant.

Even though there are drawbacks, the fixed speed wind turbine system with asynchronous generators are widely applied (maybe the most common), mainly due to the easy, durable and cheap construction, and as the wind turbine has traditionally not been concentrated to such an extent in the electric power systems that the voltage stability problems have been significant.

Applying a synchronous generator for a fixed speed wind turbine system makes the system conceptually comparable to the »standard« generator systems, featured in conventional electric power plants, including the possibility to attain control over the excitation of the rotor (and hereby the reactive power control of the wind turbine system), and may be regarded as the simplest possible concept. The control over the reactive power also provides a better possibility when it comes to attainment of stationary voltage stability, and makes the wind turbine system able (in principle, at least) to operate e.g. under islanded conditions or under black start. However, when it comes to the attaining

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[8] In a fixed speed wind turbine system with an asynchronous generator, the mechanical dynamics, caused by e.g. wind gusts or tower shadowing, are damped in the conversion to electric power, as the active power conversion relies on an acceleration of the generator rotor, not just on a change in torque (as it does for a synchronous generator). As the wind turbine blade rotor features a relatively large inertia, accelerations are slowed, resulting in a damping of the dynamics.

synchronous stability, fixed wind turbine systems based synchronous generators have some severe drawbacks, as the synchronous generator is not well suited for coping with dynamically varying mechanical power supply on the rotor. The dynamic changes in the provided torque on the rotor shaft, coming from e.g. wind gusts or mechanical oscillations in the mechanical system, will result in a more or less similar active electric power output from the generator – and in the case of large wind gusts, the synchronous generator may even be subjected to such large changes, that the generator may loose synchronism. This poor behavior of damping the dynamics of the output of the wind turbine system makes the synchronous generator inferior in fixed wind turbine systems in most appliances, apart from the fact that the synchronous generator is quite a large investment and maintenance costs are high.

Many distinct designs of fixed speed wind turbines have been developed; some with improved (or no) gear boxes, and some with improved generator systems. Yet, the basic principles and properties remain more or less the same. Wind turbine systems based on the fixed speed concept have the common draw back that it , due to their direct coupling to the electric power system, »transmit« the dynamics in the wind directly along to the electric power system and does not optimally convert the available power in the wind to electric power, as they only operate at one rotational speed and thus cannot adapt to increase efficiency. On the other hand, they are relatively simple in construction, durable and easy when it comes to maintenance, and have been proven to function well.

2.1.4. Variable speed wind turbines

One way of coping with the control of some of the dynamics of a wind turbine and to enable the wind turbine to adapt its rotational speed of the blade rotor to the actual wind conditions, is to allow the wind turbine system to have a different operating system frequency than the electric power system. Most of the concepts feature some kind of power electronic converters or inverters, which often affect the power quality of the electric power system negatively, by emitting harmonic currents to the electric power system, but also often may provide an increased possibility of control of reactive power compensation. In the simulation studies in this thesis, only fixed speed wind turbines are considered, but a brief description of variable speed wind turbines is given in Appendix G.

2.1.4.1. Clustering wind turbines in wind farms

Clustering wind turbines in wind farms can have many purposes. From a technical point of view, it may be of benefit to cluster wind turbines in a specific bounded site for e.g. to better exploit the wind at the specific site, to have some »economy of scope« when it comes to e.g. compensation gear or to justify a connection of the wind turbines at a higher voltage level. Seen from society's point of view, clustering wind turbines in wind farm may e.g. limit some of the »aesthetic« aspects of wind turbine as the »negative« effects are concentrated at a single site.

Apart from these aspects, clustering wind turbines in wind farms affects the power output from the turbines. As mentioned in section 2.1.1, the wind speed is highly dependent on time and place – this affects the production from each individual wind turbine, as turbulence and variations in the wind speed will result in variations in the wind turbine power production, causing fluctuations in the power output of the wind turbine. Such power fluctuations may, dependent on the frequency density, be hazardous to the adjacent electric power system and are as such an inferior attribute of wind turbine production (see Appendix C for a brief discussion on the power system oscillation problem).

The variations and the turbulence level of the wind may vary quite a lot dependent on the site. This applies both to larger geographic areas, for e.g. over an entire country, but also within smaller geographic areas, such as within a wind farm. Some of the variations and turbulence in the wind velocity, that one wind turbine in a wind farm is exposed to will be uncorrelated with the variations and turbulence in the wind velocity that another wind turbine is exposed to. As a result, some of the uncorrelated fluctuations in the power production from the individual wind turbines in a wind farm will level out, when considering the wind farm as a whole.

For an entire wind farm, with several wind turbines, the active power produced in the full wind farm must be defined as the sum of the productions of each of the wind turbines in the farm, i.e.

$$P_{Windfarm} = \frac{1}{2} \cdot \sum_{i=1..N} \rho_i \cdot A_i \cdot C_{P,i} \cdot {v_i}^3 \tag{3}$$

If the wind turbines are all with the same properties, the parameters related to each of the wind turbines become the same i.e.

$$P_{Windfarm} = \frac{1}{2} \cdot N \cdot A \cdot C_P \sum_{i=1..N} \rho_i \cdot v_i^3 \tag{4}$$

If it is assumed that the air density is somewhat the same within the wind farm, the total power output from the wind farm becomes

$$P_{Windfarm} = \frac{1}{2} \cdot A \cdot C_P \cdot \rho \cdot \sum_{i=1..N} \cdot v_i^3 \tag{5}$$

The term $\sum_{i=1..N} \cdot v_i^3$ then consists of wind velocities of each of the wind turbines; wind velocities that can be regarded as stochastic »signals«, that vary over time and place, and which are for, some part, stochastically uncorrelated. Thus, if each of the wind velocity »signals« are varying with a certain variation, the cumulated variance per wind turbine for the full wind farm will become smaller, as the uncorrelated variations and fluctuations between the wind turbines are leveled out. These uncorrelated variations will mainly be caused by the turbulence in the wind, and will be the faster variations. Thus, it must be expected that the faster fluctuations from the power production in wind farms are in general smaller, seen as variation per wind turbine in the farm, than for individual wind turbines.

On the other hand, clustering wind turbines in one site as a wind farm will have the consequence that multiple wind turbines are placed within a geographically small area, and will consequently be exposed to the same overall wind field, e.g. the variations caused by macro-meteorological phenomena. The variations in the wind velocity on the macro-meteorological level are usually variations over longer periods of time, and are therefore less fluctuating than the turbulence. But clustering wind turbines all in the same site has the effect that the geographic out-leveling of the slower wind velocity variations is not achieved.

Which of the above aspects that is more important depends on the actual case; however, it is usually harder to predict the turbulence that the single wind turbine is exposed to, than to predict the over all wind velocity, caused by macro-meteorological phenomena. Thus, it may be easier to predict the slow variations, caused by clustering wind turbines in a wind farm, than to predict the faster fluctuating variations caused by distributing wind turbines geographically. Hence, in many cases the benefit of clustering in wind farms is higher than the benefit of distributing wind turbines geographically. Though, consideration to both aspects may be given, simply by installing more wind farms in geographically different places.

2.1.5. Combined heat and power plants

2.1.5.1. Fundamental principles and design of CHP-plants

Designing a »silver-bullet« model of a CHP-plant, that gives a customized picture of how CHP's behave is simply not do-able, as CHP's and their operation patterns differs much from plant to plant. Thus, the modeling applied in this study has been based on more general principles based on experiences and data mainly from the Danish system operator ELTRA. The rationale for choosing ELTRA as benchmark in this case is that they (1) have a vast amount of locally based CHP's in their electric power system, and (2) could represent a comparable benchmark for the Southern Swedish area, as the demographic and geographic basis for CHP introduction is somewhat the same, with only a few large-to medium sized urban areas spread across a relatively large geographical area. These perspectives are obtained through interviews and data from plants in operation. The data used for detailed modeling is presented in Appendix I.

One of the most common type of power plant is the thermal power plants, where thermal power (e.g. from burning fuels) is converted to electric power, e.g. by using the thermal power boiling steam, that can drive a steam turbine, or by directly firing fuels in a motor, which can then drive a generator that converts the resulting mechanical power to electric power. Though, in the conversion from thermal power to electric power, not all the thermal power is converted to electric power – some remains as thermal power, and will, if not used for heating, be a loss of power. (A general reference for this section is [66], among others).

If the fraction of thermal power, which cannot be converted into electric power, is instead extracted into e.g. a district heating system, the total efficiency of the fuel will be larger, as heat and power is co-generated from the same amount of fuel. Commonly, the use of the available energy in the fuel goes from approximately 30-40% to 70-90%. To draw advantage of this better fuel efficiency, smaller plants are also made, making it possible to supply smaller heat-consumers from such CHP plants.

CHP plants can be made using different designs for driving the plant generator, such as back-pressure steam turbines, extraction condensing turbines or fuel engines[9]. To certain extend the design dictates how the plant is operated.

In a back-pressure plant, the principle is that the mechanical power source is a steam-turbine, driven by steam generated in a boiler by firing fuel(s), as shown in Fig. 5. The steam (which can be regulated by a pressure valve) passes through a turbine, which (under exchange of high-exergy power) drives an electric generator, and is hereafter condensed using a heat-exchanger, where the heat is exchanged with a system where the waste heat can be used (e.g. district heating system or an industrial process).

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[9] CHP plant designs using fuel engines, such as diesel or gas engines, are not discussed

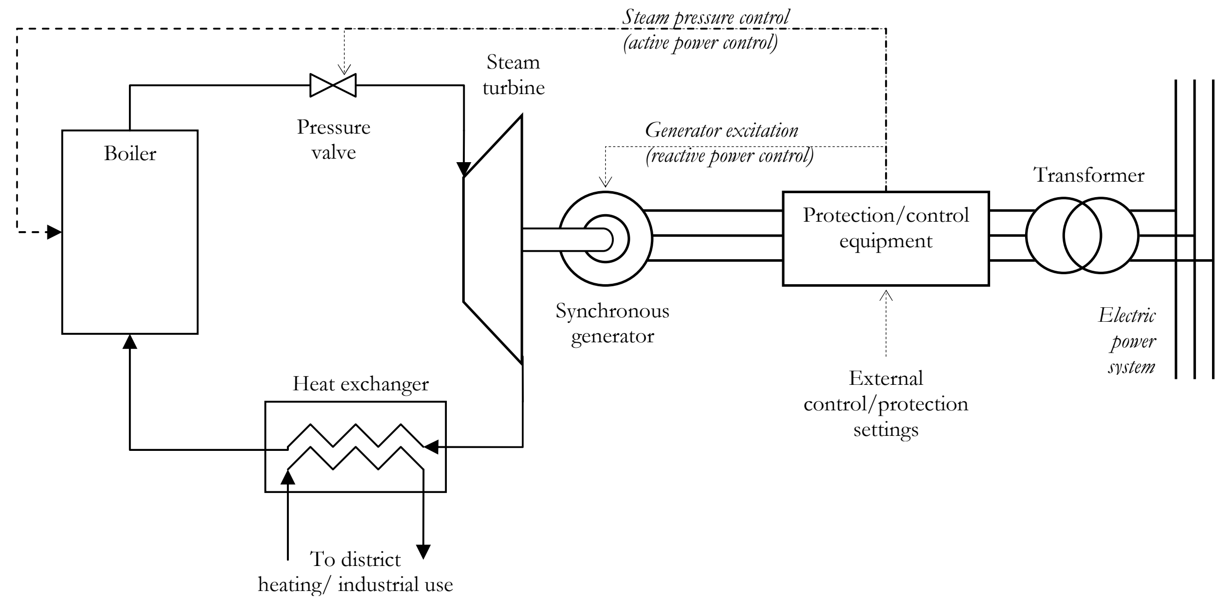

Fig. 5. Principle of CHP plant, using back-pressure steam turbine.

The back-pressure steam turbine is the co-generation turbine incarnate – it is not possible to produce electric power if no heat is produced at the same time, or reverse, as the condensing of the steam takes place in the heat exchanger that draws out heat for heat consumption. Thus, as this turbine design features this constraint, it will have a relatively high efficiency from fuel to produced heat and power, as no power can »by-pass« the system – though, it does not need a separate condenser, such as a water cooled condenser or a cooling tower, as the condensing is made by the heat-exchange. Furthermore, it is from governmental regulation easy to ensure that co-generation actually takes place in such a back-pressure CHP-plant, as single generation simply is not possible. On the other hand, from an operational point of view, this constraint makes it necessary to plan the operation in such a manner that both the heat and the power can be supplied while operating the plant.

In an extraction condensing plant, the heat for heat consumption is taken out in a system parallel to a separate condensing system, e.g. before passing through the turbine, from the intermediate pressure turbine or after the turbine, as shown in Fig. 6.

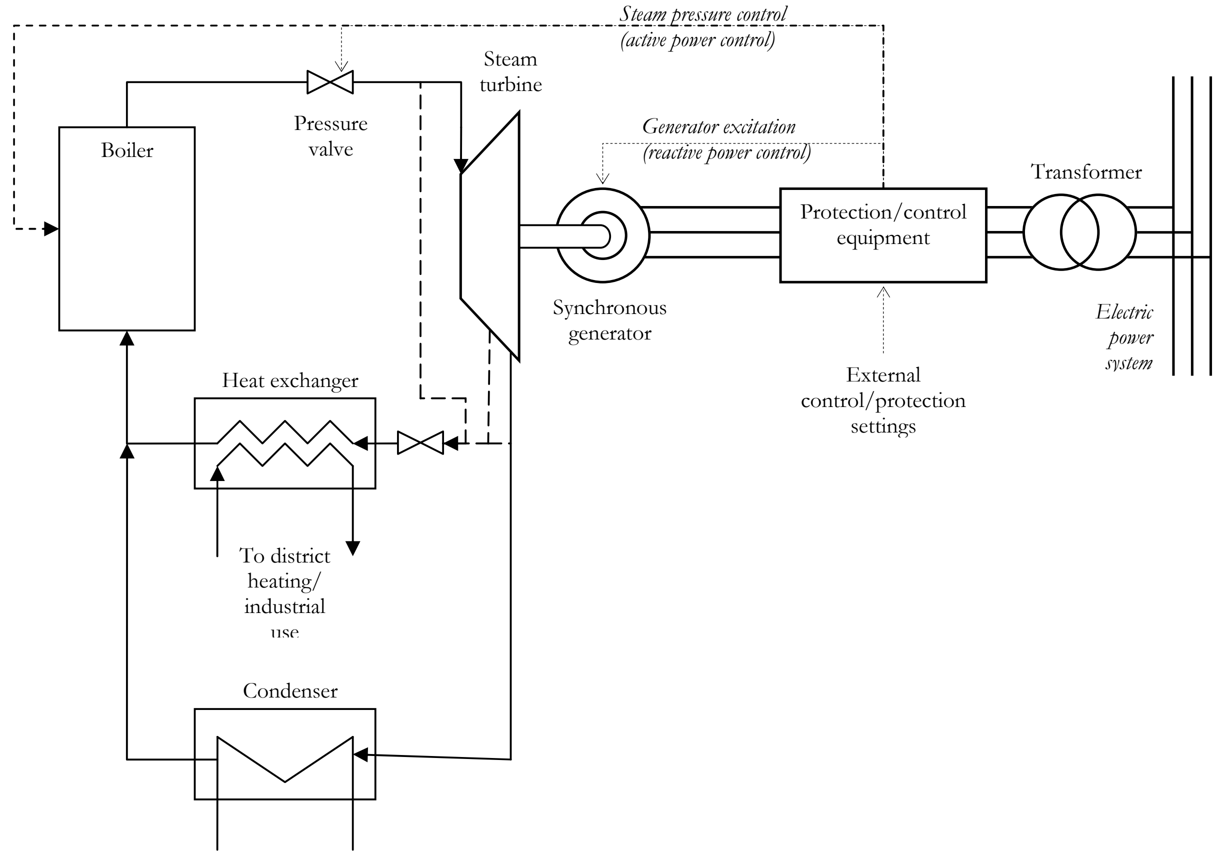

Fig. 6. Principle of CHP using extraction condensing steam turbine.

Compared to the back-pressure plant, extraction condensing plants feature the flexibility of being able to regulate the produced electric power and heat (for heat consumption) more or less independent – technically at least. Though, such extraction condensing plants demand a possibility of condensing the steam, if it is not used for heat production, and therefore a cooling device (e.g. water cooling or a cooling tower) is needed, which increases the investment costs of the plant. Furthermore, the overall efficiency, from fuel to produced commodities (heat and electric power) of the plant is lowered while running the plant in a simple condensing mode.

Both the back-pressure plant and the extraction condensing plant are commonly based on steam turbine technology, where the prime mover is steam, which can be generated from burning almost any kind of fuel, solid or liquid, dependent (of course) of the actual design of the burner of the plant.

As for wind turbine systems, it is also applicable to any CHP-plant that minimizing the investment costs have interest in order to improve the total economy of the system. And also when it comes to generators for CHP-plant application, one way of reducing the investment cost of a generator is to reduce the capability to sustain operations under faulty operations. This of course leads to the same latent problems to stability as is the case for wind turbines, that multiple tripping/fall-outs of production units may lead to instability.

2.1.5.2. Operation of CHP-plants

Regarded as economic profit units, smaller CHP-plants are usually inferior to larger power plants, as the fuel utilization in larger plants is often higher than in the smaller units – therefore CHP-plants must, in many cases rely on subsidies from e.g. the government. Whether or not a distinct CHP-plant design features the flexibility of being able to control electric power and heat production independently or not, it is often a governmental demand that a certain level of co-generation takes places in such plant (motivated by the environmental benefit from co-generation), if such a CHP-plant should receive the necessary subsidy. Thus, it is most unlikely that smaller CHP-plants are operated to produce electric power only – and often it is the consumption of heat that is the limiting factor in the production of heat and electric power. Therefore CHP-plants are typically planned and operated to meet the demands for heating, more than to meet the electric power demand.

Common for almost any kind of CHP design is that they operate most efficiently at their rated production, this is in most cases the maximum production of the plant (or close to it). Hence, an operator of a CHP-plant will have interest in operating the plant at the rated production as much as possible, however still under the constraint that the heat demand is the limiting factor in the production. Heat has the significant advantage compared to electric power (as an energy commodity) that it can be accumulated and stored – not seasonally, but over shorter periods, say 1-2 days, in heat accumulators, without unreasonable losses. Though, such stores have investment costs that are not inconsiderate. But this fact makes it possible to operate the CHP-plant to meet the total heat energy demand (over e.g. a day) instead of meeting the heating power needed at all times. Therefore, to obtain the most economical operation, a CHP-plant is typically operated so that it runs at rated production until the full daily heat energy demand has been met, where after it shuts down. It is either on or off, and only on for as long as needed to produce the necessary amount of heat energy. Besides operating in an on/off-mode, the production of electric power is will meet the highest profit – and as there no return on the production of reactive power, only active power is produced, if possible (i.e. operations at $\boldsymbol{cos(\varphi)} = 1$); thus, no reactive support is supplied to the electric power system if possible, as there is no economic reason to do so – small CHP-plants are to be considered as »free-riders« in the electric power market when it comes to voltage support.

If the CHP-plant operates under market conditions, where prices for electric power are time-dependent, the operation is of course planned in order to maximize the profit of the operation. It is important to notice, that even though either physical or governmental constraints limit the operation of a CHP-plant to adapt to the heat energy demand as the limiting factor in the production, the profit maximization from the co-generated electric power will be the most likely constraint when the production takes place. When the price tariffs are high for electric power it is more beneficial to have production – this of course as electric power cannot be stored, and therefore needs to be produced simultaneously with its consumption.

3.REAL-TIME MODEL OF WIND FARM

3.1.On the model

3.1.1. General considerations

This chapter presents an aggregate wind farm model for use in a real-time wind farm model for power system studies. The model is developed in MATLAB/Simulink to operate in real-time with the ARISTO simulator tool, but may be adapted to other simulation tools, that can interface with MATLAB/Simulink.

The purpose of this model is to provide a model, which matches ARISTO performance. The model should be able to, on basis of given voltage and given wind speed, calculate the response of the wind farm to the adjacent electric power system in real time. Thus, the model must make it possible to respond to interactions between the wind farm model, and wind speed and electric power system properties.

Modeling in MATLAB/Simulink features high flexibility and makes it possible to adapt the model to what ever is needed.

In order to enable the use of a MATLAB/Simulink model with ARISTO, it is needed to ensure that the MATLAB/Simulink model can interface with ARISTO. In short, this is done by inserting a PQ-load[10] in the electric power system model in ARISTO where the MATLAB/Simulink model is to interface with the ARISTO electric power system model, and then control the P and Q values of the load from MATLAB/Simulink. As outputs, ARISTO provides the voltage level and the phase angle at the node in the electric power system, where the load is connected. These values are used for calculating the resulting currents that flows in the equivalent wind turbine generator model, given the wind field the wind farm model is exposed to, and then the resulting exchange of active and reactive power is then calculated. These values of active and reactive power are then returned to the ARISTO

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[10] Load, where the active and reactive power are given

model from MATLAB/Simulink, and used to control the load. A more detailed description of this concept is available in Appendix J[11].

Chapter will briefly present and discuss the model, whereas a more detailed description is given in Appendix H.

3.1.2. Performance with respect to voltage stability

It is of importance to evaluate the voltage stability in relation to wind turbines and wind farm integration, especially when it comes to wind farms consisting of wind turbines based on asynchronous generator technology. The representation of the wind turbine or wind farm with respect to reactive power is of special importance, as the reactive power flow, caused by consumption or production of reactive power in the total electric power system, affects the voltage levels in the electric power system.

In ARISTO, studies are made with focus on stability in the time range 0.1 seconds to hours, i.e. some sort of dynamic stability without regarding the fast transients. Thus, the representation should be able to reflect the behavior of a wind turbine in this timeframe.

3.1.3. Performance with respect to angular and frequency stability

When it comes to the frequency stability in relation to wind turbines and wind farm integration, proper modeling is needed especially when it comes to active power, as the balance of active power is the main control parameter for regulation of the frequency. Thus, if the model should be used for frequency and angle stability analysis, it should be proper modeled especially with respect to the active power production, which in its essence is proper modeling of the wind for the wind turbine or wind farm

The representation should be able to reflect the behavior of a wind turbine in the same timeframe as considered under voltage stability.

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[11] It should be mentioned that much effort has been put into the modeling and interfacing in the project – much more than the thesis may reflect. However, focus of the thesis has deliberately been on the findings rather than the modeling, as it has been rendered that communicating the findings are of more value than describe modeling, that (as much modeling is) is very individual in its nature. The modeling work has been considered more an enabler for the enlightening the findings of the thesis than a core part of the thesis findings.

3.2. Simple modeling of a wind turbine

The wind turbines in this model are developed on basis of the so-called “Danish concept” for wind turbines. This features a fixed-speed wind turbine with an asynchronous machine as wind turbine generator. This may or may not be equipped with passive capacitor banks for compensation of the no-load reactive power consumption. However, as the model is developed in a flexible environment, other wind turbine concepts may be developed, e.g. variable speed wind turbines of various kinds.

The Danish concept for wind turbines comprises a cheap and robust wind turbine, and includes a three-bladed wind turbine rotor, a gearbox, an asynchronous machine as generator and control equipment. On the mechanical side, the rotor, gearbox and generator is mounted in a nacelle on top of a tower, and on the electric side, the asynchronous generator is directly connected (or through a regular transformer) to the electric power system.

Though it in many ways is considered rather old-fashioned, wind turbines made from this concept are the most commonly installed, even though it is generally agreed that they affect the power quality of the grid they are connected to, especially when it comes to voltage quality.

A rather simple model of such a wind turbine consists of a model of both the mechanical and electrical behavior of the wind turbine. Furthermore, a mechanical input (in terms of wind) and an electrical in- and output (in terms of the electrical interaction with the electric power system) must be made as well.

The mechanical part, the behavior of the wind turbine rotor, the gearbox and the generator rotor can be satisfactory modeled by using a two or three mass model, dependent on the appliance of the model.

For the electrical model of the generator, a regular model of an asynchronous machine may be applied.

3.3. Aggregate wind farm modeling

3.3.1. On the concept

The wind farm model is based on the aggregate wind farm principle, where an entire wind farm is represented with a single wind turbine, from which the output is then scaled up to match the wind farm. The concept is basically that a wind turbine model, consisting of a two-mass mechanical model and an electromechanical model of the generator is exposed to a wind speed signal. Given the actual voltage level and frequency of the electric power system, to which the wind farm is connected, the electromechanical model then calculates the resulting currents, and puts out the produced active and reactive power from one wind turbine. This active and reactive power signal is then scaled to match the out put from an entire wind farm, and the resulting active and reactive power outputs are then returned to the electric power system. Thus, the model can be seen as having one independent input of wind speed, two dependent inputs from the electric power system of voltage level and frequency, and returning two outputs to the electric power system of active and reactive power.

This approach demands that the wind speed, that this equivalent wind turbine representing the wind farm is exposed to contains both the turbulence already present in the wind and the turbulence generated by the wind turbines in the park themselves. In this model a previously developed stochastic model is implemented.

3.3.2. The implemented model

An overview of the implemented MATLAB/Simulink model is shown in Fig. 7.

The basic parameters for the wind farm (such as electrical data for the wind turbines, number of turbines in the farm etc.) is set in the subsystem “Wind farm/wind turbine parameters”, which simply provides data for the other subsystems of the model.

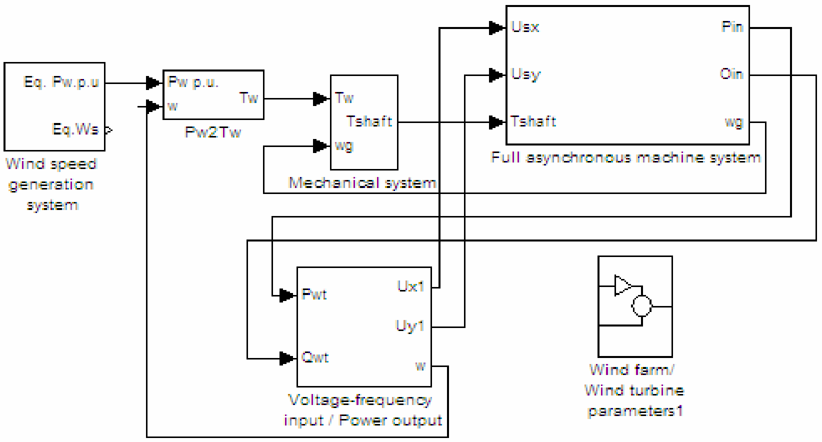

Fig. 7 Overall layout of wind farm model, as implemented in MATLAB/Simulink

An equivalent wind speed for the entire wind farm is generated in the subsystem "Wind speed generation system". This system provides an equivalent "p.u. power"-time series based on an equivalent single-wind turbine wind speed equivalent approach. This p.u.-power is then converted to a mechanical torque in the subsystem "Pw2Tw".

The electric interaction with the adjacent electric power system takes place in the subsystem "Voltage-frequency input/power output" that provides voltage level and frequency to the model, and returns the wind farm model response to the adjacent electric power system. This subsystem can be made to interface with e.g. an ARISTO model or other. From the adjacent electric power system, information about the actual voltage level and the frequency of the electric power system is provided, and the complex value of the voltage is then calculated, and the real and imaginary part is then provided for the wind model.

The torque and the voltage are then provided as inputs for the mechanical and electrical model of the wind turbine, respectively.

The mechanical model as implemented features a two-mass model, but other models may be adapted if desired. The electrical model of the generator is a basic model of an asynchronous machine. In between these models electromechanical signals are exchanged. Together, these two subsystems calculate the model response on the wind speed and the state of the electric power system, and then return it as a resulting active and reactive power.

The model concept, where the flexibility of modeling in MATLAB/Simulink is combined with the accuracy of simulating in an environment such as the ARISTO system makes it possible to perform a variety of simulations without using critical time on developing complicated models in simulation environments.

3.3.3. General on the model performance

The high adaptability of the model concept, where e.g. more specific models of protection, control systems, electric generators or wind speed modeling may be introduced by simple modeling in MATLAB/Simulink.

This feature makes it possible to re-model each distinct wind farm in a simulation case to match the actual wind farm regarded, and the possibility to perform real time simulations opens up for a whole new range of studies of mid- and long term stability. Furthermore, it makes it possible to use advanced wind farm models in training of system operators.

4.CASE-STUDY: LARGE SCALE INTEGRATION OF EMBEDDED GENERATION

4.1.Description of the Swedish power system

4.1.1. The NORDEL-system

The electric power systems in Europe are organized in several subsystems, where the system in the Scandinavian part, covering Denmark, Finland, Iceland, Norway and Sweden are part of the NORDEL system. Though it formally includes electric power systems in all of the mentioned countries, the directly (a.c.) interconnected parts which operates synchronously do not include Western Denmark (which is only connected to the rest of NORDEL through d.c.-connections) nor Iceland (which is too far away). Still, it serves as the electric power system for approx. 25 million inhabitants.

The NORDEL-system compared to European standards is a fairly well-connected electric power system, with strong transmission connections throughout the system, and with good exchange-capability with the other surrounding electric power systems in Northern Central Europe and the Baltic/Former Soviet region. Most common are transmission lines, and d.c.-connections are mostly used for connections to other larger power systems (Western Denmark is considered part of the Northern Central European electric power system), which are not operating synchronously.

The system operates at transmission voltage levels up to 400 kV (with a tolerance of +/- 10% of the nominal voltage under normal operation conditions), and at a fundamental frequency of 50 Hz (with a tolerance of +/- 0.1 Hz under normal operation conditions). Electric power generation is performed in many ways, both conventionally (in thermal, nuclear and hydro power plants) and (to a certain extent) by non-dispatchable production facilities (mostly wind turbines and CHP-plants). Politically, there has been a positive attitude towards increasing the level of non-dispatchable electric power generation, especially in Denmark and Sweden, due to a large focus on the environmental benefits from such a development.

Fig. 8 . The NORDEL-system

4.1.2. The Swedish power system

Due to the geography, the Swedish part of the NORDEL electric power system is more or less the »back-bone« of the system to which all the other system parts are connected. Thus, it contains most of the available generation and most of the transmission capability. However strong, the transmission grid in the Swedish part of the NORDEL-system suffers from »bottle-neck« phenomena, which limits the transmission and complicates the attainment of stability in the electric power system.

In general, three »cut-sets« are considered in the Swedish system.

- The transmission lines between Finland and Sweden (»the north-east cut-set«)
- The transmission lines between the Northern part of Sweden (north of Stockholm) and the central-east part (»the central cut-set«)
- The transmission lines between the south-western part of the system (from Gothenburg, southwards to Skåne , Halland and Blekinge) and the central-east part (»the southern cut-set«)

These three cut-sets separate the overall transmission power system in Sweden in four parts, between which the transmission capacity is limited, stretching the system stability under critical conditions, especially when it comes to voltage stability.

The main kinds of electric power production in the Swedish are hydro power and nuclear power production, with the hydro power mainly concentrated in the northern part of the system, and with the nuclear production concentrated in four production facilities in the southern, central and northern part of the system. The remaining power demand is covered by thermal production units (mainly oil, coal and gas-plants), and to a limited extent by CHP-plants near larger cities and wind power.

The transmission electric power system is organized as a meshed system on voltage levels of 400 kV, 220 kV and 130 kV, which interconnects production and consumption areas on the top level. From this, a radial layout distribution electric power system, operating at 50kV to 10 kV, further distributes the power down at consumer-level, which normally is 0.4 kV.

4.2. Local Impact of wind power and CHP on electric power systems

4.2.1. Overview of investigated properties

As discussed in section 2, both wind power and CHP have an impact on the electric power system, that such production facilities are connected to, as they exchange (active and reactive) electric power with the electric power system. This of course have an impact on the electric power system performance locally.

The response to introduction of wind turbines may relate either to the properties related to the exchange of active or reactive power with the power system, where the exchange of active power mainly affect the frequency or angular stability and the exchange of reactive power mainly affect the voltage stability. Both the stationary and the transient stability of these may be considered. The character of the impact may vary, from hazardous impacts, which may lead to loss of load, to less significant problems, mainly affecting e.g. the voltage quality in the local region.

The synthesis on the results obtained in this thesis is deliberately made qualitatively rather than with a great deal of quantification. The rationale for this is two-fold

– The simulations in this case study was defined long before there was any indication of what changes with regards introduction of wind turbines and CHP in Southern Sweden could occur in the future. Examples of this are that at the time of defining the case study there were no plans or decisions that outlined the replacement of Barsebäck with neither CHP or wind power on large scale in Southern Sweden – and even though plans for closing down the second reactor of Barsebäck existed, there was political uncertainty of whether it would happen on time or not[12]

– Due to the extensive degrees of freedom in the definition of the case study, quantitative results obtained on e.g. regional level in the simulations are highly dependent on the geographical location and installation of both CHP and wind turbines. Thus, due to these uncertainties, there is a

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[12] Thus, the span of the degrees of freedom with respect to the definition of the case study is so large that a joint reference group and student rendered that results were more suited for qualitative synthesis rather than quantitative, simply to ensure the validity of the conclusions

latent risk that a more quantitative synthesis of the results, and thereby more quantitative conclusions may distort the findings made in the study

It may be argued that presenting a power system simulation study without a great deal of quantitative reporting is untraditional; however, the issue-driven top-down approach taken in this study justifies this, as the focus should then be in the insights identified, not the numbers.

4.2.2. Impact of wind turbines

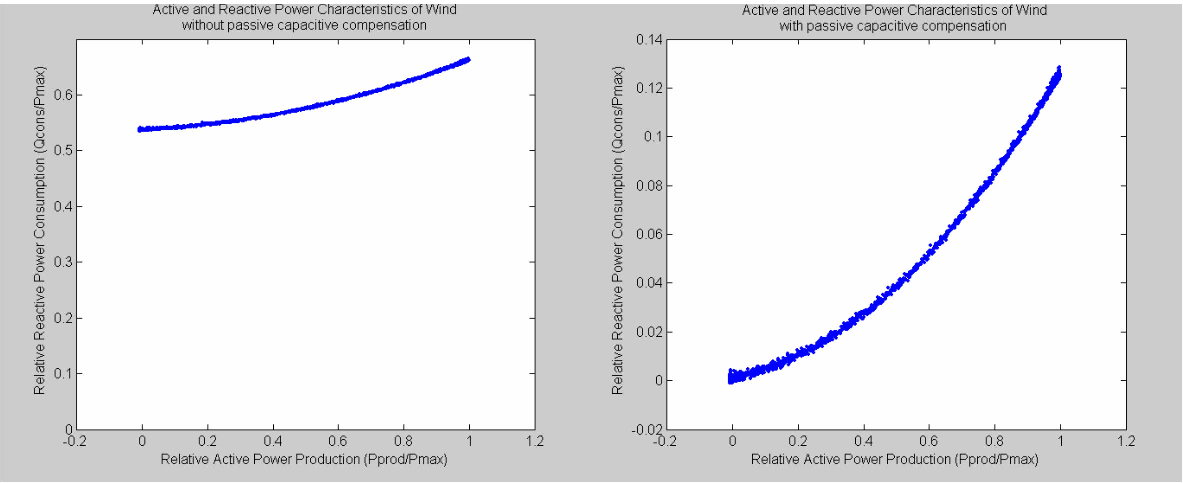
Although the local impact of wind turbines have been studied in detail previously, it is still important to keep in mind, that the local impact is significant. It has in previous work been found (1) that wind turbines have a rather high impact on the reactive power balance locally which increases with increased production from the wind turbine, and (2) that the effect of the wind turbine structure (especially the tower – thus, usually known as the »tower shadowing«-effect) on the aerodynamic properties, and the resulting turbulence of the wind, have a significant impact on the electric power output, though the impact of this effect is reduced with higher wind speeds. Laypeople have often hypothesized over the impact of the »tower shadowing«-effect in wind farms, assuming that this effect increases with wind speed – however, it has not been possible to find support for this hypothesis. Recent research indicates the opposite [72]. The higher the number of wind turbines, and the higher the wind speed, the less relative impact of the »tower shadowing«-effect. These effects are modeled into the wind farm models used in this project, assuming these effects to be a proven fact.

However, to fully understand the impact of wind turbines in an electric power system, it is worthwhile to put effort in investigating these properties to stress their importance, even if it can be argued as investigating the models applied more than investigating new findings.

4.2.2.1. Local stationary voltage stability

Whenever a wind turbine is stationary producing, the amount of power produced affects the voltage level in the locality, to which the wind turbine is connected. What affects the most is the production/consumption profile of reactive power for the wind turbine.

In this thesis wind turbines designed after the classical Danish concept is treated. These can, as discussed in 2.1.2.1, be equipped with some kind of static reactive power compensation, usually in terms of capacitor-banks, with »passive« capacitors that can just be switched on or off all together, in a size that compensate for the magnetization. Equipping a wind turbine with such static capacitor compensation changes the active and reactive power characteristic for the wind turbine significantly. Using the wind turbine model described in Appendix H, this change can be calculated for a wind turbine, as illustrated below in Fig. 9.



(a) ***(b)***

Fig. 9. Active and reactive power production/consumption characteristic for a wind turbine, calculated using the wind turbine model from appendix G without and with static magnetization compensation; (a) the characteristic of a non-compensated wind turbine, (b) the characteristic for a static compensated wind turbine.

As can be seen in Fig. 9, the static compensation removes »the bias« consumption of reactive power. Thus, nominally, the reactive power consumption is reduced significantly. Most Danish concept wind turbines produced today have some kind of compensation of the reactive power consumption from the magnetization of the rotor, and therefore the most likely power production/consumption characteristic is as shown in Fig. 9 (b). Still it can be seen that even with this static compensation, the wind turbine generator consumes reactive power during production, at a rate that marginally can be estimated to approximately 10-15% of the produced active power. Depending on the characteristics of the adjacent electric power system, this may result in voltage variations along with the variations in wind turbine power production, unless some kind of dynamic compensation is introduced.

In the Danish and Swedish regulations it is given that voltage variation from wind turbines may not exceed 5% [70] of the rated p.u. voltage at the point of connection of the wind turbine. An approximate estimate of the voltage variation in a point, ***i,*** to which a wind turbine that produces an amount of active power of $\boldsymbol{P_{wt,i}}$ and consumes an amount of reactive power $\boldsymbol{Q_{wt,i}}$, is connected can be calculated as p.u.-value (of the rated voltage $\boldsymbol{U_{rated,i}}$ of the connection point)

$$\Delta U_{p.u,i} = \frac{\Delta U_i}{U_{rated,i}} \approx \frac{R_{system,eq.i} \cdot P_{wt,i} + X_{system,eq.i} \cdot Q_{wt,i}}{U_{rated,i}} \qquad (6)$$

where $\boldsymbol{R_{system,eq.i}}$ and $\boldsymbol{X_{system,eq.i}}$ are the Thevenin-equivalent impedances in a simple one-line representation of the entire electric power system, and they are closely connected to the present short-circuit power of the electric power system in the point ***i*** that can be calculated as

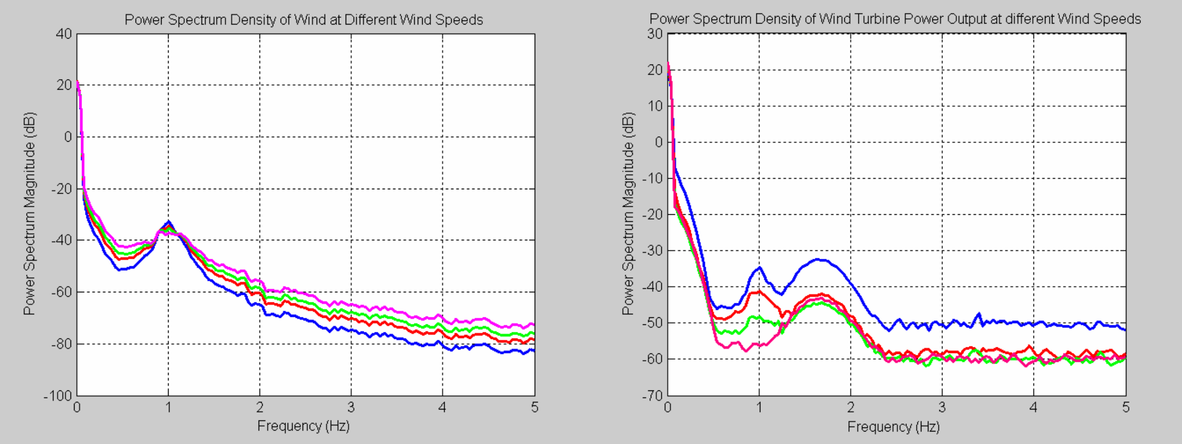
$$S_{k,i} = \frac{U_{rated,i}^2}{\sqrt{R_{system,eq.i}^2 + X_{system,eq.i}^2}} \approx \frac{U_{rated,i}^2}{X_{system,eq.i}} \quad \text{for } R_{system,eq.i} << X_{system,eq.i} \qquad (7)$$

Assuming this and given a certain characteristic for the production of active reactive power in a wind turbine, the demand for short-circuit power can be calculated in order to maintain the voltage variations within a given limit. Thus, there exist a criterion for the demanded level of short-circuit power needed to keep voltage variations within acceptable limits, that is given by the voltage level of the system and the wind turbine active and reactive power production characteristic.

4.2.2.2. Power fluctuations from wind turbines and wind farms

The fluctuations in power production from a wind turbine are mainly caused by fluctuations in the wind, as discussed in 2.1.1ff. These variations are then transformed (»filtered«) according to the wind turbine properties, as the power in the wind is transformed into electric power in the wind turbine.

A way of illustrating the content of fluctuations in the wind and a power output from a wind turbine is to calculate the power spectrum density of the active power output. This is done for the wind used in the wind farm model described in Appendix H, and for the active power output from the wind turbine, at different levels of mean wind speed.



(a) ***(b)***

Fig. 10. Relative power spectrum densities of wind and wind turbine active power output, at different mean wind speeds (blue lines: at 8 m/s, green lines: 12 m/s, red lines: 15 m/s, purple lines: 20 m/s – all signals are relative signals); (a) power spectrum densities of wind from wind farm model. The »spike« at 1 Hz is due to turbulence generated from e.g. tower-shadow (also known as »the 3-p-component«), (b) power spectrum densities of wind turbine output. The »spike« at 1 Hz is the 3-p-component, and the »hump« at approx 1.75 Hz is due to mechanical oscillations in the wind turbine, between wind turbine rotor and generator rotor. It can be seen that the relative content of 3-p-component in both the wind and the wind turbine power output is reduced with larger wind speeds, whereas the fluctuations in the power output from the wind turbine, caused by the mechanical oscillations between wind turbine rotor and generator, still are present.

As it can be seen from Fig. 10, the wind contains turbulence, generated by the wind turbines in the farm mainly from the revolving of the wind turbine blade tips, resulting in wind power content at a frequency that corresponds to the revolving of the wind turbine blades (the »3-p-component«). Thus, it can be seen that this effect is leveled out the higher the overall wind speed is, as can be seen from Fig. 10 (a) – the higher the average wind speed, the less significant is the turbulence from the revolving wind turbine.

If the active power output from the wind turbine is considered, it can be seen that the oscillations in active power production has a power content that comes from the turbulence in the wind generated by the revolving wind turbine (the »spike« noted in the caption for Fig. 10 (b)), and a power content that comes from the inter-mechanical power oscillations in the wind turbine (the »hump« noted in the caption for Fig. 10 (b)). Apart from these distinct oscillations, the general power content at other frequencies in the wind is reduced to a lower level. It can be seen that at higher wind speeds, the active power output oscillations that comes from the wind turbine generated turbulence in the wind are relatively lowered, whereas the relative content of inter-mechanical oscillations remains. It can furthermore be seen that the higher wind speed, the lower the relative power content of oscillations coming from the general level of turbulence.

The frequencies at which the wind turbine generated turbulence in the wind and the inter-mechanical power oscillations, respectively, have their content, relies on rather basic wind turbine properties.

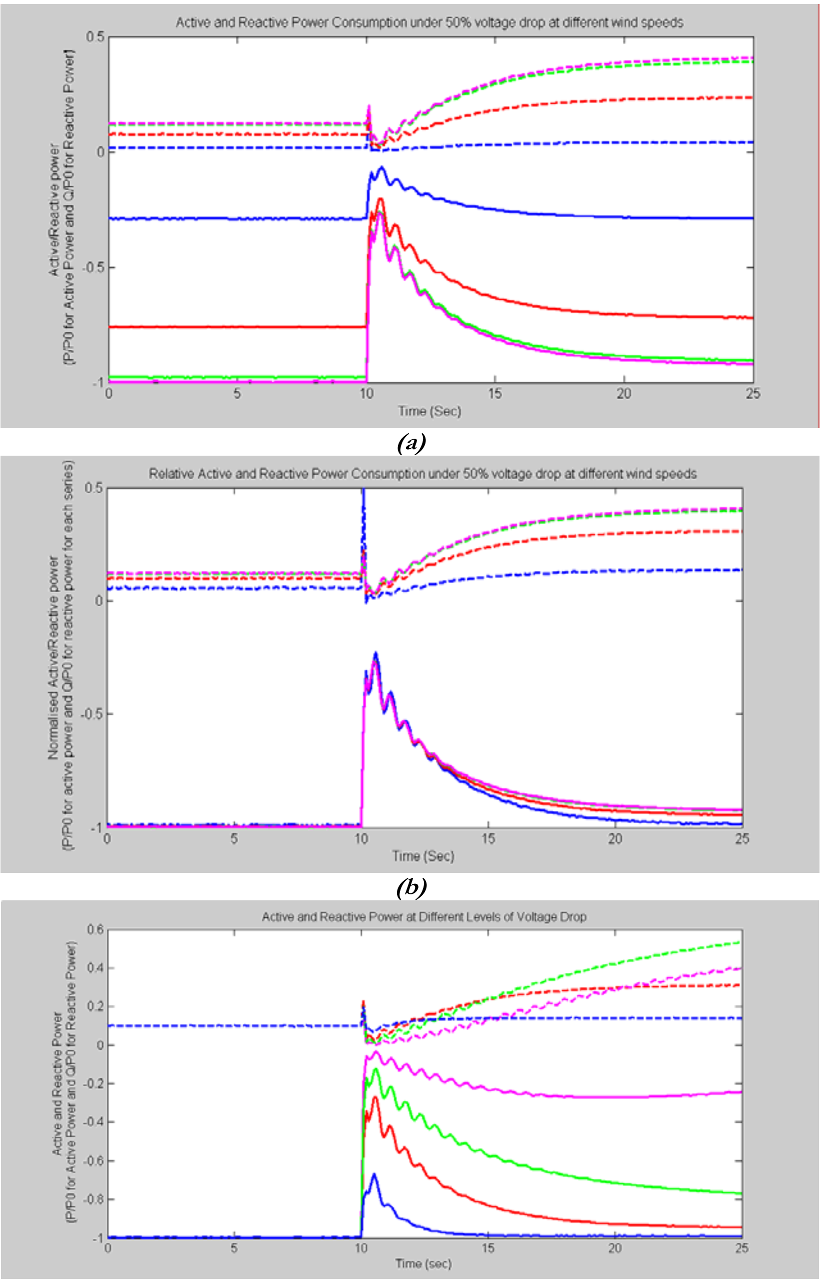
The wind turbulence, generated by the revolving of the wind turbine blades and the rotational speed that the wind turbines revolve at, determines the frequency at which the wind turbulence has its power content (i.e. the »spike«). This applies for both the wind turbulence and the resulting power output. Thus, changing the gearing between the wind turbine rotor and the wind turbine generator, and hereby changing the rotational speed of the wind turbine rotor, makes it possible to change the frequency of the turbulence, so that the larger the gearing ratio, the slower the revolving of the wind turbine rotor and the lower the frequency of the turbulence, and vice verca.

The inter-mechanical power oscillations in the wind turbine are dependent on the stiffness of the shaft between the wind turbine generator and the wind turbine rotor. The stiffer the shaft, the higher the frequency and the faster the oscillations will be, and vice versa.

Hence, if there is a latent risk that active power oscillations from the wind farm may trig power system oscillations in the neighboring electric power system, it is possible to design the wind turbine to “avoid” having power oscillations in these frequency ranges, by changing simple parameters as gearing in the wind turbine and the shaft stiffness.

4.2.2.3. Response on voltage drop

Sudden voltage drops, caused by e.g. switching or faults in the electric power system, occur often and can have an impact on the operations of the wind turbines. Due to the design with the asynchronous wind turbine generator, the reactive power consumption will especially change, as can be seen in Fig. 11



(a)

(b)

(c)

Fig. 11. Response on active power (dotted lines) and reactive power (solid lines)of wind turbines connected to an infinite bus, when exposed to voltage drops, at different wind speeds – (blue lines) 8 m/s, (red lines) 12 m/s, (green lines) 15 m/s, (purple lines) 20 m/s (a positive value means production, a negative value consumption); (a) Actual active power production and reactive power consumption over time, with a voltage dip of 50% occurring after 10 s, (b) Same as (a), but with the power values normalized to 1 in their initial values, (c) Actual active power production and reactive power consumption over time, with a voltage dip of 80% occurring after 10 s.

As can be seen in Fig. 11 (a), when a voltage drop occurs, the active power output and the reactive power consumption drop immediately as a consequence of the lowered voltage. The higher the wind speed, the higher the pre-voltage dip power flow, and the higher the nominal power flow drop under the voltage drop. The oscillations in the power output are mainly caused by the mechanical oscillations. As the mechanical power into the system, i.e. the mechanical power from the wind, is not altered by the voltage drop, the power, which is not exchanged with the electric power system, is used for accelerating the wind turbine rotors, thus increasing the electric current in the wind turbine generator. Hereby the power output is increased, and power stability is attained. After a while, active power production is up to almost the same level as before the voltage drop – only the increased losses caused by the increased current level makes the difference. Though, with regards to the reactive power there is a notable difference between the pre-voltage dip and post-voltage drop power levels, which can be seen better from Fig. 11 (b). Whereas the active power is almost restored at the same level, the reactive power consumption of the wind turbines are highly increased, mainly due to the increased currents in the wind turbine generator. And noteworthy is also the fact that the higher the wind speed, the higher is the relative increase in reactive power consumption. And, as can be seen from Fig. 11 (c), where a 80% voltage drop is simulated, the higher the voltage drop, the higher the reactive power consumptions increases. If the generator was exposed to faults having a shorter time, the isolated impact in voltage stability seem from the generator would be smaller.

This increased reactive power consumption may be hazardous to the operation of the electric power system that the wind turbines are connected to, as it may lead to reactive power unbalance and ultimately to voltage collapse. In Fig. 11 (c) it can be seen how, in this specific case where the wind park is connected to an infinite bus, an 80% voltage drop lead to an unstable increase in reactive power consumption for wind speeds of 15 m/s and 20 m/s, whereas the stability is maintained at wind speeds of 8 m/s and 12 m/s.

Thus, it must be stated that when exposed to voltage drops, the reactive power consumption will increase, and the larger the voltage drop, and the higher the wind speed, the larger an increase in reactive power consumption, whereas the active power production is restored after a transient period. The larger the dip and the longer it lasts, the higher the impact.

The results in Fig. 11 are highly dependent on the properties of the chosen wind turbine generator. For larger asynchronous generators it is not uncommon to see generators with stall torques around ~2.3-2.5 of the rated torque of the generator. If e.g. the voltage drops 50%, the stall torque may drop to as low a level as 50% of the rated torque of the generator – the result of this is that overspeeding is then more likely to occur. With larger wind turbines with consequently larger generators there is a risk of a potentially increased impact of the wind turbines on the electric power system reactive power balance.

4.2.3. Impact of CHP

As discussed in section 2.1.5, CHP's are essentially designed as smaller conventional thermal power plants, though with operation planning on basis of the heat needed to be produced rather than on basis of the electric power needed. Further more, to improve the efficiency of the plant, most CHP's are operating in "Off/on-operation" meaning that they are either not producing any power at all or producing at its maximum limits, and are focusing on producing active power only, as it is the most profitable.

However, the plants are normally fully equipped with most of the control systems that are normally also installed in larger power plants, such as voltage regulation and excitation systems, speed governering systems and power system stabilizers. So, they are capable of supporting the electric power system regionally with MVAr support and others. But as CHP owners are usually not compensated for this kind of support, these are usually not active.

The "Off/on" production scheme and the lack of incentives to support the electric power system with MVAr's of course have an impact on both the long term operation of the electric power system, as the other production facilities are to compensate for the "loss" in production, caused when the CHP-plant closes down or commence production. In larger electric power systems, with plenty of other production facilities are available, this is usually not a stability issue.

The capability of supporting the electric power system in transient operations is though available, and therefore this is taken into account in this study. As can be read from Appendix I where the specifications for the CHP-models used in this study are given, many electric power system control features are specified, and when used in this study, the CHP's are implemented as conventional power plants in the simulation tool. Thus, the impact on local level is the same as of any other conventional power plant in the simulations, and as they do not differ from other power plants in principle, they are not treated further.

4.3. Impact of wind power and CHP on the Swedish electric power system

4.3.1. Overview of investigated properties

The two investigated cases shows how a replacement of the Barsebäck nuclear power plant with either 100 % wind turbines or a combination of 50% wind turbines and 50% CHP would affect operations in the southern Swedish electric power systems under both stable and faulty operations, considered on transmission level with respect to dynamic and stationary stability.

The simulations are performed using the Nordic 32 test system and the Sydkraft test system, with modifications.

The Nordic 32 test system features a simplified view of the Nordic system with more details in Sweden. It has 32 buses and models the relatively long distances in the Swedish electric power system. It has implemented rather good dynamic models, and proves diversity in dynamic phenomena. This makes it rather suitable for initial studies of how the dynamic influence of large scale introduction of wind farms in the Swedish electric power system will be. The Nordic 32T test system is a standard Cigre system, for which the properties can be found in [71].

The Sydkraft test system features a more detailed modeling of the southern Swedish electric power system on 400 kV and 130 kV level, whereas the mid and northern Swedish electric power system is less detailed (though still more detailed than the Nordic 32 test system). This model contains rather detailed information about the southern Swedish system, which is considered confidential by Sydkraft. The specific details about this system can not be described, but the electric power system model contains good dynamic models of the power system behavior, though tap-changer operations and under-voltage protection schemes are not included, and thus not considered in this analysis. The Sydkraft test system is an internally used model produced by the Swedish power company Sydkraft AB, and thus the details are considered confidential.

The modifications made to the original Nordic 32 test system and the Sydkraft test system are the equivalent Barsebäck generator with wind farms and CHP equivalent capable of producing the same amount of electric energy, calculated on a yearly basis.

As there are currently no plans for such a large scale implementation of wind power or CHP’s in the Swedish electric power system, the size of the introduced wind farm equivalents and CHP’s are based on rough estimations.

As a rough estimate, the remaining Barsebäck plant has a yearly operation time of approx. 7500 hrs. a year, and with a maximum power output of 600 MW. If it is estimated that an average wind farm has an operation time of 3500 hrs a year, this corresponds to an installed capacity of 1500 MW of wind turbines. This amount of installed wind farm power is modeled using wind farms consisting of wind turbines with a nominal power output of 2 MW, based on the Danish concept wind turbines. Similarly, when modeling the 50% wind turbines and 50% CHP case, the amount of CHP-power installed is calculated on a rough estimate, using an operation time of 6000 hrs. a year. Thus, in the 50% wind turbine and 50% CHP case, Barsebäck is replaced with 750 MW installed wind turbines and 375 MW of installed CHP. The wind turbines are modeled as described in chapter 3 and Appendix H.

In the Nordic 32 test system, the wind farms and CHP’s are clustered all together in one substation in Southern Sweden, and in the Sydkraft system, the wind farms are divided up in three individual wind farms of 500 MW rated power each, one near Barsebäck, one near Karlshamn and one near Gothenburg. When CHP’s are introduced, they are placed in the same places, in clusters of 125 MW of installed power respectively. The CHP’s are modeled as shown in Appendix I.

The performance of this electric power system is analyzed under the following conditions:

- Response under wind blow up
- Response under wind fall down
- Response under line fall-out
- Response under unit tripping
- Response under 3 phase fault

4.3.2. Simulation results

4.3.2.1. Simulation under stable conditions

The simulations investigations performed under stable conditions include

- Response with stable wind conditions and no faults
- Response under wind blow up and no faults
- Response under wind fall down and no faults

The observations through the simulations are summed up the result tables in Appendix K, in section K.1

When simulations are performed with stable wind conditions and no faults, simulations indicate no problems, but a slightly lowered voltage level in the southern part of Sweden, which is easily coped with by voltage regulation, is observed. It is of particular interest that the simulations indicate no wind farm caused trigging of the un-damped power oscillation modes that are known and present in the Nordic electric power system and are caused by electro-mechanical oscillations between generators in the southern Sweden and the Norwegian and Finnish grids. Normally, these oscillations have frequencies at approx. 0.2 Hz- 0.7Hz. As the power fluctuations from the wind farms are relatively low due to stochastically out-leveling, and as the 3-p component has a frequency of 1 Hz, as well as the mechanical oscillations between wind turbine rotors and generators have even higher frequencies, they trig none of the oscillation modes. However it cannot be concluded that the latent risk of trigging of power oscillations is not present under other conditions, for e.g. in slower revolving wind turbines or other load conditions. It is most likely when wind turbines become larger, and revolve slower, this problem changes from being a hypothetic problem to a real problem. As can be seen in the simulation example in 4.3.2.3 power system oscillations are present in the simulation; however they do not lead to instable conditions.

Under stable conditions when the wind blows up or falls down, the voltage profile in the southern part of the electric power system is stressed. This is due to the consumption of reactive power under production in the wind turbines. The voltage is significantly lowered when the wind blows up, and significantly rises as the wind falls down. The reason why this phenomenon occurs is that the layout of the Swedish electric power system, that has some “bottle-necks” from the northern parts that have plenty of production and voltage regulation capability, to the southern part, which lacks voltage regulation capabilities.

Introducing 50% CHP and reducing the installed wind turbine power to 50% makes the situation better, but still, voltage problems are present.

From the simulations in the Sydkraft electric power system it can be seen that in the specific cases, the voltage problems during stable operations are less significant, though still present, when the wind turbines are connected on 400 kV level compared to when they are connected to 130 kV level. This, of course, is due to the higher over-all short circuit level at 400 kV-level.

4.3.2.2. Simulation under faulty conditions

The simulations investigations performed under faulty conditions include

- Response under line fall-out
- Response under unit tripping
- Response under 3 phase fault

The simulation results from these investigations are summed up in tables in Appendix K, under section K.2.

Common for the investigations made under faulty conditions is that they all lead to the same problem. When the electric power system is stressed with a fault the problems with maintaining the voltage level in the southern part of the Swedish system are increased, and in many cases cause fall-out of substations due to local voltage collapses. Voltage regulation tries to recover the voltage, but with the wind farms still being present in the power system or not after the fault, it cannot keep up. After approximately 1 to 1½ minute, the voltage collapses in many cases.

The situation is less severe when it comes to voltage problems when the wind farms are connected to 400 kV level than when it is connected to 130 kV level. Similarly, reducing the amount of wind turbines to 50% and introducing 50% CHP makes the situation even better, and in many cases keeps the system from entering a state of voltage collapse. Still, the voltage stability problem is eminent.

In line with the observations from 4.2, the there is an increased negative impact on the voltage stability with higher wind speeds, and larger and longer dips in voltage caused by faults.

4.3.2.3. Simulation example: study with 100% wind turbines and a unit tripping

4.3.2.3.1. About the study

One of the performed studies is a case, where the Barsebäck plant is replaced with wind turbines, that covers 100% of the yearly energy production, i.e. a total amount of 1500 MW rated wind turbine power in southern Sweden, in terms of wind farms. The wind turbines are no-load compensated with passive capacitor banks, and the total wind farm production is calculated from an average wind speed of 8 m/s, thus the wind turbines do not produce at their rated level.

In this simulation, a study of the Swedish electric power system on transmission level is carried out, and the study concerns a situation where a unit tripping occurs. The used power system model is the Nordic 32T-test system, except that the Barsebäck equivalent is taken out, and an aggregate wind farm is introduced in southern Sweden. In this system, the Sealand part of the system is modeled as a unit (as well as other aggregations are made) – as the wind power is installed in southern Sweden, and what is considered worst case is voltage collapse due to mismatch of reactive power production and consumption, the more critical incident that may occur is the loss of the nearest unit, which is the Sealand equivalent.

4.3.2.3.2. Before the unit trips

The situation in the electric power system before the Sealand unit equivalent is tripped can be described as more or less stable. As can be seen from Fig. 13 (a) and Fig. 14 (a-c) in the time range -30 s to 0 s, the overall voltage profile is stable, and the voltage levels are within reasonable boundaries of the rated voltage.

Some active power oscillations of the magnitude approx +/- 40 MW with an oscillation frequency of approx. 0,04 - 0,05 Hz are present in the electric power system, which can be seen from Fig. 14 (d) in the time range -30 s to approx +10 s. Taking part in this active power oscillation are (among others) the Oskarshamn and Ringhals equivalents on one side, and the Sealand and Forsmark equivalents on the other side[13]. From supplementary simulation studies with and without the wind turbines connected it can be learned that these power oscillations are caused by the wind turbines, though they do not them selves take part in the oscillations. Furthermore, from the supplementary simulation studies there are no indication that these oscillations lead to angular instability them selves, but they maintain their magnitude of approx. +/- 40 MW, if not disturbed (as done in this study by a unit tripping).

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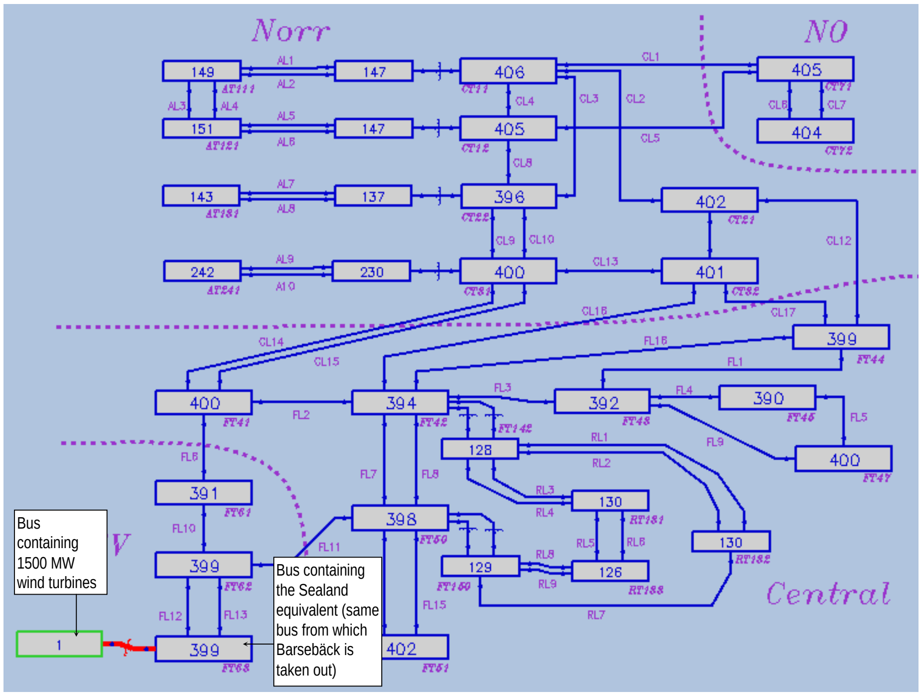
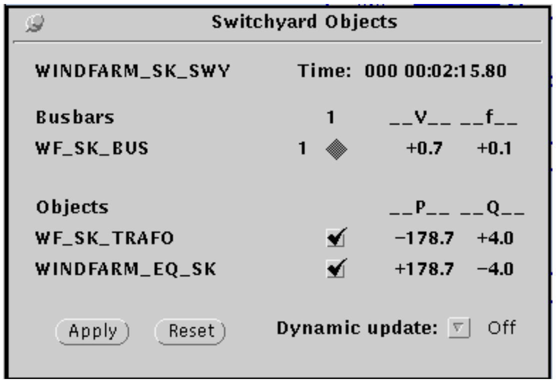
[13] As not all active power outputs from generator units are shown, the oscillations shown in Fig. 14 (d) do not match eachother.



Bus containing 1500 MW wind turbines

Bus containing the Sealand equivalent (same bus from which Barsebäck is taken out)

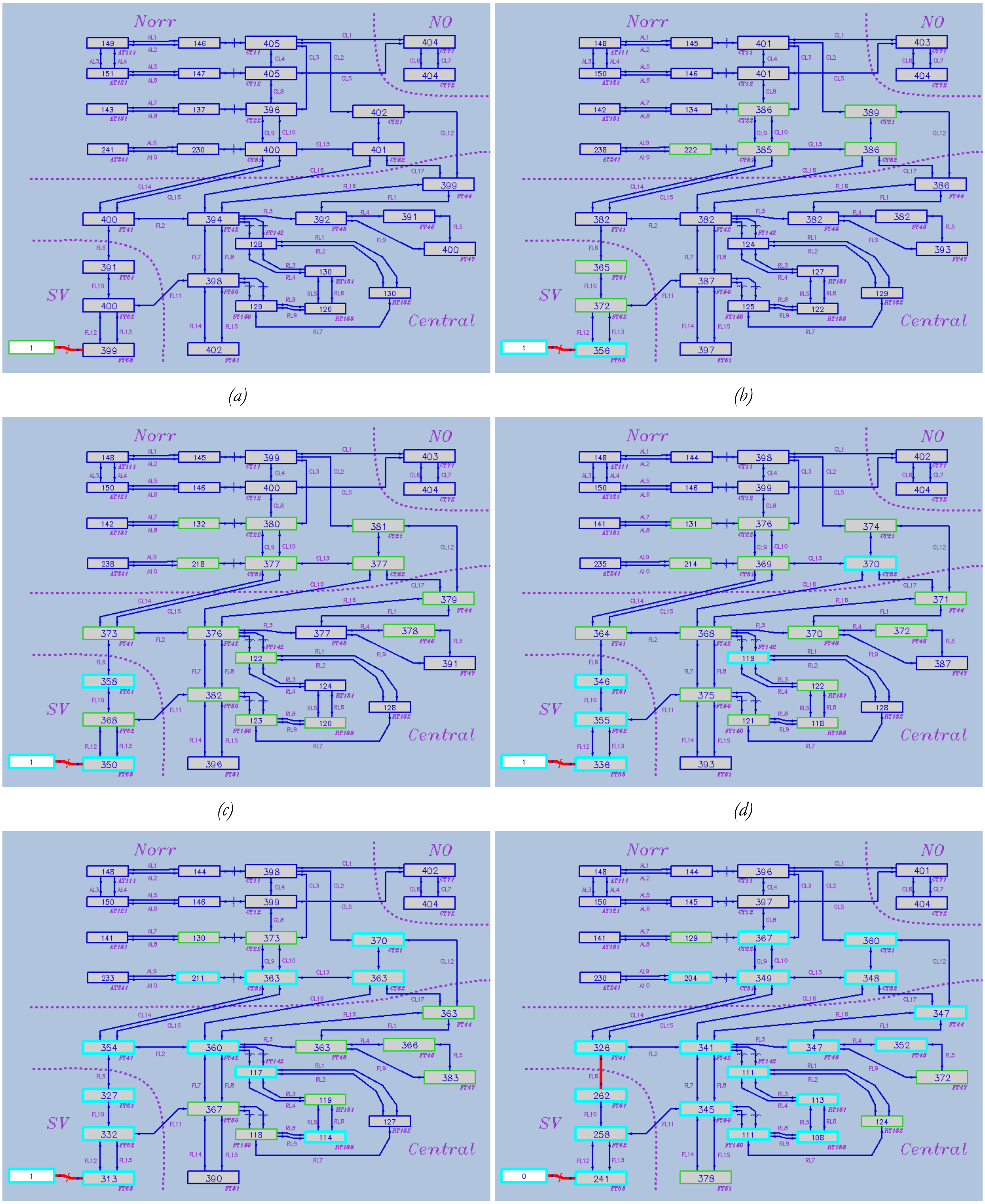
(a)



```
WINDFARM_SK_SWY              Time:  000 00:02:15.80

Busbars                      1      __V__  __f__
WF_SK_BUS                  1 ◆       +0.7   +0.1

Objects                             __P__  __Q__
WF_SK_TRAFO                  ☑      -178.7  +4.0
WINDFARM_EQ_SK               ☑      +178.7  -4.0

                         Dynamic update: ▽  Off
```

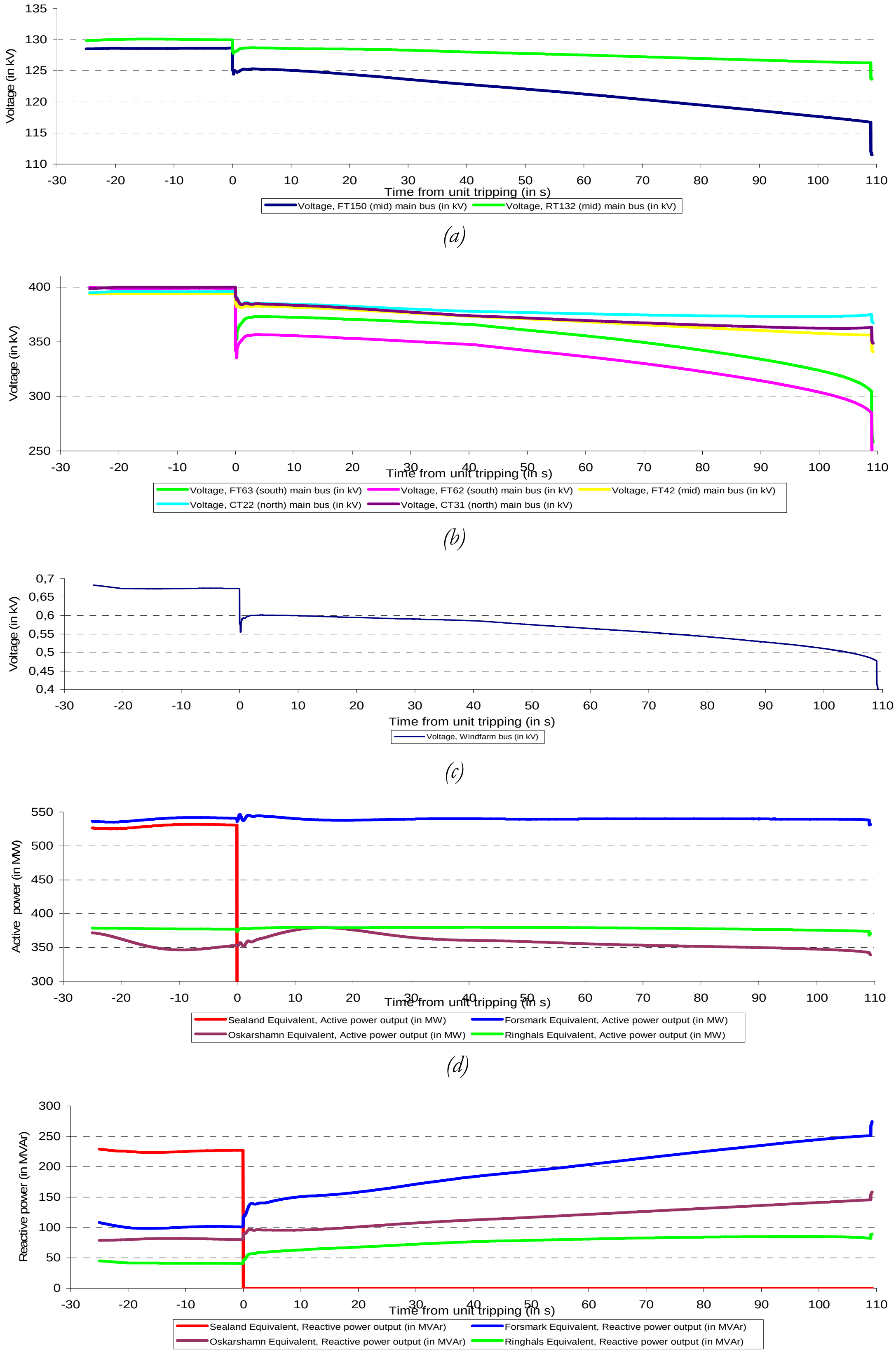
(b)

Fig. 12. The simulation system; (a) Screen-dump from ARISTO showing the Nordic 32T test system – the numbers in the busses are approximate voltage levels in kV, (b) conditions at the wind farm bus.



(a) (b) (c) (d) (e) (f)

Fig. 13. ARISTO-screen dumps from unit-trip simulation study – numbers in buses are voltage level in kV; (a) status before unit tripping, (b) status just after unit tripping, (c) status after 30 s, (d) status after 60 s, (e) status after 90 s, (f) status just before final voltage collapse.



(a)

(b)

(c)

(d)

(e)

Fig. 14. Simulation data over time (selected voltages and power outputs) – the time 0 s indicates the time when the tripping occurs. Names refer to the Nordic 32 T test system, which can be seen in Fig. 12; (a) voltage levels at selected 130 kV-buses in mid Sweden, (b) voltage levels at selected 400 kV-busses in south, mid and north Sweden, (c) voltage level in wind farm equivalent, (d) active power production from selected generator unit equivalents, (e) reactive power production from selected generator unit equivalents.

4.3.2.3.3. After unit tripping

When the Sealand unit is tripped at time 0 s, (of course) the unit active and reactive power output immediately drops to 0 (as can be seen in Fig. 14 (d)). This immediate drop in reactive power has a direct impact on the voltage profile in especially southern Sweden (which can be seen in Fig. 13 (b) and Fig. 14 (a-c)), where the voltage levels drop approx. 10-15% of the rated level.

The loss of reactive power production in Southern Sweden results in a mismatch of reactive production and consumption, which leads to a drop in voltage levels, that spreads to more and more parts of the system as can be seen from the ARISTO screen dumps in Fig. 13 from (b) to (f). As can be seen from Fig. 14 (e), the other units in the electric power system react by increasing their reactive power output, trying to compensate for the loss in order to maintain the rated voltage at their respective voltage regulator busses.

As can be seen from Fig. 14 (e) the selected units more or less doubles their reactive power production, and locally the voltage drop is ended after approx. 90-100 s. (as can be seen in Fig. 14 (b) CT22 and CT31 voltage records) whereas the voltage still drops uncontrolled in the mid and southern regions. After approx. 110 s, a voltage collapse occurs in the southern Swedish electric power system.

4.4. Identified problems

Introduction of wind power in the Swedish electric power system may invoke mainly two problems

- Problems with maintaining voltage stability, both under stable and faulty operations.
- Latent problems with risk of trigging of power oscillation modes

The reason why the voltage collapses is easily identified. When wind turbines based on the Danish concept are exposed to a fall in voltage level, which all of the above mentioned faults cause, their consumption of reactive power increases. This increase in reactive power consumption causes the voltage level to drop further, and ultimately causes a voltage collapse.

5.MEANS OF COPING WITH THE IDENTIFIED PROBLEMS

5.1.About the identified problems

The problems identified from the simulation studies summed up in chapter 3 can be said to refer directly to the type of wind turbines modeled in the wind farm. Although new technologies are available, the Danish concept wind turbines are still the most commonly installed type of wind turbines, and are still installed in large quantities, e.g. in the new wind farm in the southern part of eastern Denmark (Nysted wind farm). The reason why this technology is still applied is that it is cheap and reliable in operations on wind turbine level. Thus, the identified problems are highly relevant.

5.2.Technical means of coping with the voltage problem

5.2.1. Disconnection

One easy, but not very promising way to deal with the voltage problem under faulty operations is to disconnect the wind turbines when faults occur, as their reactive power consumption is then removed along with the active power production. This strategy however has two draw backs that does not make this an option: Firstly, if wind farms are to replace conventional power plants in larger scale, they must be able to support the electric power system under faulty operations as well as stable operations, and disconnection is therefore not desirable. Secondly, this does not deal with the voltage problems that occur under stable conditions.

System operators will probably in the future demand from wind farm operators that the wind farm stays connected to the electric power system and support the system in a similar way to what can be expected from a conventional power plant. Thus, it must be demanded that an increased control of the reactive power consumption is introduced, making the wind farm at least reactive power neutral under all kinds of operations, or better so that it should be possible to support the electric power system from the wind farm with production of MVAr's.

5.2.2. Capacitor-based full load compensation

The voltage stability problems related to the wind turbines occur because the wind turbine generator increases its reactive power consumption under certain operation conditions. With regards to the stable conditions where voltage problems occur as a consequence of increased active power production and the resulting increase in reactive power needed to magnetize the asynchronous generator rotor, it seems reasonable to simply increase the passive capacitor-based reactive power compensation supplied in each wind turbine in the wind farm, so that the capacitors are dimensioned to supply the full load reactive power needed by the wind turbine generators.

This has been tested in some supplementary simulation studies. The results show that this takes care of the voltage problems that occur due to wind blow up under stable conditions. However, under wind blow down under stable conditions, where the wind turbines losses load, a risk of over voltages instead is introduced. In the investigated simulation studies no severe over-voltage problems have been identified, but voltage increases up to 10-12% have been identified. Still, depending on the properties of the electric power system to which a full load compensated wind turbine is connected, and the penetration level of wind turbines in the electric power system, over voltage problems may occur.

Another aspect relevant to consider when discussing compensating to full load using passive capacitors is the fact that the reactive power produced in the capacitors is highly dependent on the short-circuit power level in the point of connection, and is proportionate to the square of the voltage level. Thus, if a voltage drop occur in the electric power system due to e.g. a faulty operations in the electric power electric power system, the reactive power produced is decreased in the same very moment where it is needed to prevent the asynchronous generator of the wind turbine from lowering the voltage in order to be able to supply itself with reactive power. Consequently, there is a risk that full-load capacitive compensation can not support sufficiently to prevent under voltage problems or ultimately a voltage collapse. Simulations carried out on 130kV level have indicated this.

5.2.3. Introducing new types of wind turbine generators

Introducing new wind turbine generator technologies, that are capable of controlling the reactive power flow, is a possible way of coping with the voltage stability problem. If a generator concept that makes it possible to fully control the reactive power flow to the wind turbine generator is introduced the problem is principally no longer eminent. Some wind turbine generators, which are capable of controlling the reactive power flow, are mentioned in Appendix F and Appendix G. Generator concepts that should be specially mentioned are the synchronous generator and the doubly-fed induction generator.

5.2.4. Integration of wind turbines with conventional generation and compensation systems

From the simulation studies made with 50% CHP and 50% wind turbines, it can be seen that the voltage problems are not as severe. Of course, the impact of the wind turbines is reduced as the penetration level is halved, but still the introduction of the CHP and the possibility to compensate with reactive power when under voltage problems occur makes it a possibility. However, in order to benefit from such an integration, the mode of operation of the CHP is important; it must be ensured, either through regulation or through economic incitement that the CHP is operated to supply with reactive power.

Two conventional ways of performing reactive compensation should also be mentioned: The synchronous condenser and the SVC. The SVC is basically switched capacitors with rather sophisticated power electronics and control equipment, and the synchronous condenser is basically just a regular synchronous machine with no active load but with voltage regulation still active.

Simulations have been carried out using the former Barsebäck-generator (i.e. the one, which is “substituted” by the wind turbines and CHP’s), and these simulations indicate that by introducing this synchronous machine as a synchronous condenser, most of the voltage instability problems under both stable and faulty operations can be coped with.

5.3.Technical means of coping with the risk of power oscillations

The problem with the latent trigging of power oscillations modes can be solved with a similar demand to level out the power fluctuations from the wind farm, and to specify a frequency band and maximum level of active power fluctuation content within this frequency band which the active power output from the wind farm may not exceed.

There are many ways of coping with a latent risk of trigging power oscillation modes already in the design phase of the wind farm. Some of the newer wind turbine concepts feature means of leveling out power fluctuations by either active stalling/pitching of the wind turbine blades, or by introducing generator concepts that enable increased control of the active power flow from the individual wind turbine and thereby from the entire wind farm.

Furthermore, if the wind farm is to support the electric power system when the unit trips with active power support, it is necessary to be control the active power from the wind farm so that it can be increased in case of frequency drop. As it is impossible to control the winds, the only way to obtain such a possibility is lower the production of the wind farm to an active power output that is lower than (say 80-85%) [59]of the possible output. Thereby, a “spinning reserve” is obtained, that enables increased production of active power when needed to support the electric power system operations.

5.4.Business structural aspects

5.4.1. Rethink the task of delivering power

No doubt that the technical problem of attaining a stable voltage profile in the southern Swedish electric power system has to be solved by technical means. If the system is short of reactive power, it must be compensated for. Technical problems demand technical solutions. The problem however this, that these solutions don‘t come for free. Who has to pay the bill? And how do »we« - regulators, electric power companies, customers, politicians – decide which level of e.g. voltage stability that »we« have to go for? And at what price? And how do we take care that those consumers, who don’t affect the voltage stability by consuming vast amounts of reactive power, are not left to pay for those who do?

Electric power is not just electric power. It has a quality that is influenced by many factors that include maintaining a stable voltage. Quality aspects of power are discussed in Appendix D and liberalization aspects of power quality is discussed in Appendix E.

The reason why maintaining a stable voltage is considered a task for regulators is that it is not considered as a special feature which is taken into account when pricing the delivered power. Maybe as part of a tradition, customers have only been billed for their consumption of active power, and not for their impact on the overall voltage-profile of the adjacent electric power system – i.e. primarily their respective consumption/production of reactive power.

However tradition or not, the traditional billing of active power only has made the problem of maintaining voltage stability a problem for regulators only. This task includes »mind-reading« of customers demand and gain of improved voltage stability, and the resulting planning of how much should be invested to improve voltage stability and at which costs. But if liberalization has to have any meaning, these factors have to be determined by the liberalized market, not by regulators. If the political decision of liberalizing the electric power markets have to turn out as successfully as possible a full liberalization has to take place, including liberalization of the task of maintaining stable power system conditions – and by this is not meant privatizing the ISO’s, but to liberalize the market conditions.

In the case study, where wind turbines replaced the Barsebäck nuclear power plant in southern Sweden, what turned out to be the main problem was the attainment of a stable voltage profile in southern Sweden, as it was hard to balance production and consumption of reactive power.

Regarding maintaining voltage stability, an establishment of a liberalized reactive power market would work to balance the production and the demand in the long run – this, of course, to the extend, that the market dictates. Not to the level decided by engineers at the ISO or to politicians who after e.g. a blackout demands the ISO to improve standards, and afterwards either won’t pay the costs or complains that the customers have to pay.

The power business has to rethink their role, from being a provider of a governed infrastructure to the offerer of a service with different quality levels governed by a market.

5.4.2. Reactive power has a value

Most reactive power production takes place in one of either two basic ways: Either it is produced in a electric power generator (usually a synchronous generator) or in some sort of capacitor-bank based compensation gear (either as more or less sophisticated power electronics or as regular passive capacitor banks). Reactive power has a cost either way it is produced[14]

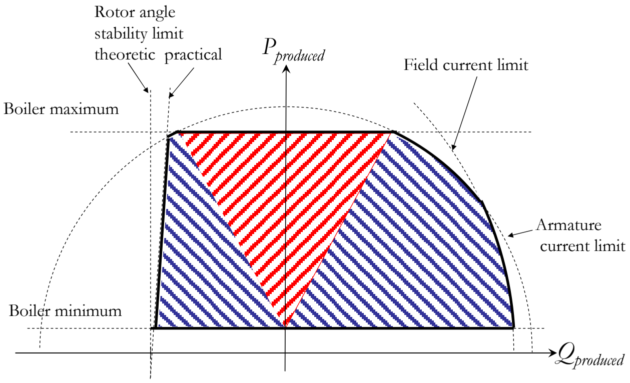


Fig. 15. Synchronous generator unit production limits. Red area indicates the production area where there is no lost opportunity by increasing reactive power production, blue areas indicates production areas with potential lost opportunity

In synchronous machines, the production of reactive power is basically controlled by the level of magnetic excitation in the field winding at the rotor. The production capability is determined, together with the production capability of active power, by the electric power generator units properties i.e. limited by the factors shown in Fig. 15. From this figure, it can further be learned that in some production areas there is a lost opportunity if reactive power production is increased, as it limits the possible active power that may be produced. The cost of producing reactive power in a electric power generator unit must include some fixed costs, such as depreciations on the equipment

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[14] What is discussed here is only the cost and value of reactive power – not the pricing. The actual pricing has more elements than costs, e.g. a producers demand for a pay-off from being available, for providing flexible service, etc.

and installations needed to operate (e.g. buildings) and a maintenance and administration overhead, and some variable costs that include the potential lost opportunity of producing more active power. These measures are measures that can be accounted, so that the producer can come to some knowledge of his cost structure, when offering reactive power to consumers.

Equally, production of reactive power in capacitor banks or equally has a cost. But as there is no lost opportunity or no other variable cost that depends directly on the production level, the cost structure is less complicated, as it only includes the fixed costs of depreciations, maintenance, etc.

Furthermore, there is transmission costs connected to bringing the reactive power from where it is produced to where it is to be consumed. These costs include at least three kinds of costs: Depreciations and maintenance costs on transmission gear, lost opportunity costs, as the transmission of reactive power (of course) limits the amount of active power that may be transmitted through the same lines, and losses. Whereas depreciations and maintenance can be regarded as fixed costs, the costs related to lost opportunity and losses are variable costs that increase with the amount of reactive power. Regarding the transmission losses related to transmitting reactive power, it should be mentioned that the losses actually are not a cost itself, but invokes a cost in production, as the reactive power that is lost during transmission has to be produced elsewhere, with the costs that this may inflict.

To the customer, buying reactive power has a crucial value. The reactive enables the user, whether it is a system operator or an end user with a washing machine, to operate the equipment. And the more reactive power available, the more equipment can be operated.

This does not make the consumers sitting ducks, that can be targeted and hold up to buy reactive power at any price. Customers have a at least two strategies that can reduce their cost of reactive power: Reduce their total reactive power consumption and/or produce the reactive power them selves. To produce reactive power by your self actually may be feasible under some conditions, as it does not demand the same large investments as the production of active power. Dependent on the consumer demands, the reactive power can be produced in e.g. a smaller generator (that can also be used for emergency production during blackouts) or capacitor banks, on the consumer side of the installation.

Studies in India [82] indicate that wind farm operators are concerned about this, in their choice of compensation system. In one Indian state, where wind farm operators have to pay for their reactive compensation, the reactive power consumption from the wind farms is eliminated, whereas wind farm operators in Indian states, where reactive power is supplied as a free commodity, there is a significant consumption and little incitement to replace compensation gear as e.g. capacitor banks when they fail. The observations of this behavior supports the hypothesis that increased economic incitements will yield a significant impact, and thus accentuates the need for developing a liberalized market for reactive power.

5.4.3. Things to pay attention to with liberalizing reactive power

Important to remember when discussing the introduction of a liberalized reactive power market is that the introduction of a market solves no problems it self; still technical problems have to be solved by the use of technical solutions. What the market may help with is to define who has to pay for the services provided, and to sharpen the awareness among consumers and producers of how much is actually needed. And the market can, in the long run, ensure the balance between reactive power production and consumption that actually adds value to the users of the electric power system. If a consumer has to pay for reactive power, the consumer will have the incentive only consume what actually adds value to him – contrary to the case, where the reactive power is provided for free.

When regarding wind turbines specifically, the result of a liberalized reactive power market would result in the wind turbine owner having an incentive to reduce his consumption of reactive power; simply because every MVAr would cost the owner. Thus, the owner would be interested in finding out how to serve his demand of reactive power at the lowest price for existing wind turbines, and would ask for wind turbines that have the lowest operation costs, including the cost of other MVAr consumption – both would improve the operation of the electric power system, that the wind turbines are connected to. More, it would drive wind turbine manufacturers to produce wind turbines that have less impact on the electric power system when it comes to reactive power.

Though, some drawbacks are of course also to be taken into account.

Introducing a market of reactive power may not be a popular decision. Most consumers would consider it an extra cost, and they will have an interest in obstructing the market development. And as the gains from a liberalized reactive power market are gains on long term, the immediate consequence of liberalization may not gain to the customer, but actual costs. As is the case for devices that are introduced in an electric power system, the introduction of a liberalized reactive power market will also introduce some market »transients« before start working properly.

Noteworthy is also that where active power losses can be reduced by increasing the cross section area of the conductors in a transmission line, reducing reactive power losses is much more complicated, as reactive power losses are determined by the reactance of the transmission line, that again is highly dependent the total distance of the lines used in the transmission. And even though the configuration of the conductors along the transmission lines have an influence of the reactance of the line, it is hard to reduce reactive losses, and the losses connected to the transmission of reactive power are rather large compared to transmission of active power.

These transmission costs makes reactive power a different commodity than active power; whereas active power can be transmitted with rather low costs over long distances, making it a »global« or »system wide« commodity, reactive power is a much more »local« or »regional« commodity that has to be produced in a certain proximity of the consumer.

6.CONCLUSIONS

6.1.Conclusions and contributions

The work in this thesis tries to uncover aspects of a future large-scale integration of wind turbines or a combination of wind turbines and CHP's, and to uncover aspects of how this integration can take place in a liberalized Swedish power system.

As no actual plans exist for such large scale integration at the time of the thesis, the thesis has investigated a self-made case study, investigating the impact of a replacement of the Barsebäck power plant by an equivalent amount of wind turbines or an equivalent amount of wind turbines and CHP in combination. This case study is used for qualitative analysis.

The case study is carried out in the real-time simulation environment ARISTO, and for this purpose a wind farm model, that can operate in real-time and interface with ARISTO has been developed. It is believed that a real-time model for simulating wind farms is new. The model developed is based on the Danish concept wind turbines and the model principle is based on the aggregate wind farm modeling, where wind farms are modeled as an equivalent single wind turbine. The model is developed in MATLAB/Simulink, which makes it easy to adapt to other kinds of wind turbine concepts than the Danish concept. Thus, the model developed is flexible with respect to future development.

The investigations in the case study are carried out in local and system level, where the local level simulations investigate the properties of the wind farm and CHP and the simulations on system level investigate the impact of the wind farm and CHP on the system.

Regarded on local level, the wind turbines have the most impact compared to CHP. Whereas CHPs are essentially just small conventional power plants operated in an "on/off"- production scheme, wind turbines have an impact on the local voltage stability and an impact with power fluctuations. As Danish concept wind turbines are equipped with asynchronous generators, they consume a considerate amount of reactive power during the production of active power, which may affect the reactive power balance in the local area where they are connected. When exposed to voltage dips, the consumption rises even more, which threatens the attainment of reactive power balance, as the electric power system is usually weakened when voltage dips occur. Furthermore, the fluctuations in the active power from the wind turbines may affect the system stability as it may trig power system oscillations. From the simulations and from previous studies it can be learned that the main components in the fluctuating active power output from the wind turbines are caused by the »tower shadowing«-effect and from inter-mechanical power oscillations between the different mechanical components in the wind turbine. Whereas the »tower shadowing«-effect is weakened with an increased wind speed, the inter-mechanical power oscillations remain their relative magnitude. It may be argued that these individual findings are not new, but it is important to stress the importance of keeping these findings in mind when building a perspective on the impact of wind turbines and CHP on electric power systems on system basis – and this an important take-away. Also it is worthwhile mentioning that level of impact of integrating the wind turbines with regards to voltage stability is highly dependent on the rated power of the generator.

When regarded on system level, where wind turbines or wind turbines and CHP in combination are replacing Barsebäck in the southern Swedish electric power system, the same pattern found in the local investigations show on system level. Studies are carried out under both stable and faulty conditions, and in the case study, the problems related to this large scale integration are problems with maintaining voltage stability under both stable and faulty conditions, and latent problems with the trigging of power system oscillation modes. In some studies the voltage stability problems end up in voltage collapses, caused by the reactive power production of the wind turbines. The power oscillation problems do not cause the trigging of instable power oscillation modes. This because the investigated wind turbines do not have an power output, that oscillates in the frequency range of these modes, but have a much higher frequency. Though, as wind turbines are increased in size, and therefore revolve slower and all together change mechanical parameters, there is a potential risk that the power oscillations caused by tower shadowing effect or the inter-mechanical power oscillations may alter frequency, to a frequency that can trig oscillations in the electric power system where integrated.

To encounter the problems that are identified in the case study, the introduction of means to control the reactive power flow is needed, as discussed in chapter 5. One easy way is simply to introduce full-load reactive compensation of the wind turbines, as discussed in 5.2.2, but other kinds of technical means of coping with these problems, such as introduction of new wind turbine generator concepts or co-integration with conventional generation or compensation systems, are among the possible solutions. When it comes to facing the potential threat of wind turbines trigging power system oscillations, this problem can be encountered by proper wind turbine design. The wind turbine revolving and the design of the mechanical parts of the wind turbine (mainly the generator - wind turbine rotor shaft stiffness) can be chosen to avoid fluctuations in the active power output in a frequency range that may trig power system oscillations.

What is more interesting to discuss is how to ensure that these means are actually taken, as the solutions for these problems does not come for free. As the electric power business is structured today, only active power flow is considered valuable, and thus the only commodity that has to be accounted for. This leads to a lack of focus on the other services that have to be provided in order to make the electric power system function properly, including a lack of interest from commercial actors to take part in balancing the reactive power production and consumption. As discussed in section 5.4.2 reactive power has both a cost in production and a value to the consumer, and thus there is basis for a market which can help to balance the reactive power in the long run.

Liberalizing the delivery of reactive power will give consumers incitements to reduce their impact with respect to reactive power consumption to a minimum, as well as ensure that the demanded production capacity will be available. The fact that developing economic incitements for increased reactive power compensation has an inpact on the operational scheme of e.g. wind turbines is supported by observations in India. In the case of wind turbines, this will give incitement for the wind turbine owner to reduce the reactive consumption, which again will invoke a demand for wind turbines with less impact on the electric power system with respect to reactive power.

6.2. Future work

The study of this PhD-thesis has been on top level, and in more aspects more intended to be an »eye-opener« than a »subject-closer«. This, of course, because there at the time of the study were no specific plans for a large scale integration of wind turbines and CHPs. Thus, there are subjects that could be studied in deeper detail.

6.2.1. Modeling studies

The model for wind farms that has been developed in this PhD-study has be based on the aggregate wind farm concept and on wind turbines of the Danish concept type equipped with no-load reactive power compensation. Though, many new wind turbine concepts has been developed over the years , e.g. wind turbines with variable generator concepts, with more sophisticated reactive power compensation, more sophisticated active power control, etc.

As already mentioned in the introduction, modeling of these types of wind turbines in a wind farm is important going forward, if it is desired on a later stage to investigate these wind turbine concept and their impact on the electric power system when integrated. A pilot study focusing on evaluating new concepts in parallel, with the “Danish concept” as a benchmark, could even represent value, especially if the commercial aspects of the development stage of the wind turbine concepts is included.

6.2.2. Simulation studies

In this study, a case study of a fictitious replacement of the Barsebäck power plant by either wind turbines or a combination of wind turbines and CHP. However interesting, this case study is fictitious, and so are its presumptions.

From this point of view, the actual quantitative conclusions that can be drawn from these simulation studies, are sparse, as they do not refer to any actual cases. Hence it is needed to study in greater detail the actual plans for wind turbine and CHP integration, when they are available. Increased detail level of the analysis could be introduced e.g. by including tap-changer operations and power system protection schemes in the dynamic behavior of the electric power system, if needed to conduct a study focusing in the issues related to these properties. Also the impact of the size of the generator of the wind turbine (as mentioned in section 4.2.2.3) could be a topic to investigate further, if relevant in a future study evaluating alternative wind turbine concepts.

6.2.3. Liberalization aspects

The thesis and its appendices also treats liberalization aspects of integration of wind turbines and CHP, and especially discusses the need for liberalization of other commodities, services and qualities of power than just the active power delivery. As there it has been decided politically all over Europe that the electric power businesses has to be liberalized, it is important to investigate how to liberalise fully in all aspects.

The studies that might be needed to fully understand how liberalization can take place are many. There is a basic need to find out how the different commodities, services and power quality features actually adds value to consumers, and how the cost structure of providing and serving them are. There is a need to find out how to trade the commodities, and how to ensure good market functionality. Also it is needed to investigate how this liberalization may affect the daily operation of the electric power systems and the development of the electric power system.

7.REFERENCES

[1] V. Akhmatov, H. Knudsen, A.H. Nielsen, N. K. Poulsen and J. K. Pedersen, ”Short-term Stability of Large Scale Wind Farms”, Proceedings of European Wind Energy Conference EWEC, paper PG3.56, Denmark, 2001

[2] V. Akhmatov, H. Knudsen and A.H. Nielsen, ”Advanced simulation of windmills in the electric power supply”, International Journal of Electrical Power and Energy Systems, Vol. 22, Issue 6, Elsevier, pp. 421-434, 2000

[3] V. Akhmatov, A. H. Nielsen and H. Knudsen, “Electromechanical Interaction and Stability of Power Grids with Windmills”, Proceedings of the IAESTED International Conference on Power and Energy Systems, ISBN: 0-88986-300-8, pp. 398-405, Spain, 2000

[4] V. Akhmatov, H. Knudsen, M. Bruntt, A. H. Nielsen, J. K. Pedersen and N. K. Poulsen, ”A Dynamic Stability Limit of Grid-connected Induction Machines”, Proceedings of the IAESTED International Conference on Power and Energy Systems, ISBN: 0-88986-300-8, pp. 235-244, Spain, 2000

[5] V. Akhmatov, “Analysis of Dynamic Behavior of Electric Power Systems with Large Amounts of Wind Power”, PhD-thesis, Ørsted-DTU, Section of Electric Power Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, 2003

[6] J. Arrillaga, M. Bollen and N. R. Watson, ”Power Quality Following Deregulation”, Proceedings of the IEEE, Vol. 88, No. 2. pp. 246-261, 2000

[7] G. Asplund, K. Eriksson and K. Svensson, “HVDC Light – DC Transmission based on voltage sourced converters”, ABB Review No. 1, Sweden, pp. 4-9, 1998

[8] G. Asplund, “Application of HVDC-Light to Power System Enhancement“, 2000 IEEE Power Engineering Society Winter Meeting, Conference Proceedings (Cat. No.00CH37077), Vol. 4, pp. 2498-2503, 2000

[9] N. Athanasiadis, J. R. McDonald, G. M Burt and C Booth, “ Dynamic FACTS Modelling: Methodology and Validation Using the Voltage Stability Problem”, Proceedings of Universities Power Engineering Conference UPEC ’98, Vol. 1, pp. 234-237, 1998

[10] M Bruntt, J. Havsager and H. Knudsen, “Incorporation of Wind Power in the East Danish Power System“,International Conference on Electric Power Engineering, PowerTech Budapest 99, p. 54, 1999

[11] Dansk Standard, ”Elproducerende Vindmøller Del 12: Teknikker til Måling af Ydelse”, Danish Standard no. DS/EN 61400-12, 1st ed., Denmark, 1999

[12] ELTRA Information, “Power Quality Improvements of Wind Farms”, Søndergaard Bogtryk & Offset, ISBN: 87-90707-05-2, Fredericia, Denmark, 1998.

[13] J. Fan and S.K. Salman, “The Effect of Integration of Wind Farms Into Utility Network on Voltage Control due to the Co-ordination of AVC Relays”, Fourth International Conference on Advances in Power System Control, Operation and Management. APSCOM-97. (Conf. Publ. No. 450), Vol. 1, pp. 260-265 , 1997

[14] A. Feijóo and J. Cidrás, “Modelling of Wind Farms in the Load Flow Analysis”, IEEE Transactions on Power Systems, Vol. 15, No. 1, pp. 110-115, 2000

[15] C. Flavin and N. Lenssen, “Reshaping the Electric Power Industry”, Energy Policy, Vol. 22, No. 12, pp. 1029- 1044, 1994

[16] P.Gardner, N.Jenkins, R.N. Allan, Z.Saad-Saoud, F.Castro, J.Roman, and M. Rodriguez, “Network connection of large wind turbines”, Proceedings of the 17th BWEA conference on Wind Energy Conversion, pp. 161-6, 1995

[17] P. Gardner, “Grid Connections of Wind Turbines”, International Power Generation, Vol. 18, No. 2, p 58, p. 60 and p. 63, 1995

[18] R. A. George, “Status of Tubular SOFC Field Unit Demonstrations”, International Journal of Power Sources, Vol. 86 No.1-2, Elsevier, pp. 134-39, 2000

[19] A. D. Hansen, P. Sørensen, L. Janosi and J. Bech, ”Wind Farm Modelling for Power Quality”, Proceedings of IECON’01 Conference, ISBN: 0-7803-7108-9, pp. 1959-1964, 2001

[20] E. Hau, “Windturbines”, Springer Verlag, ISBN: 3-540-57064-0, Berlin, Germany, 2000

[21] Hausler, M.,“HVDC Light-a new converter for DC transmission”, Elektrizitaetswirtschaft, Vol. 97, Issue 21 , p. 38 and pp 40-4., 1998

[22] Häusler, M., “Connecting offshore wind farms to the grid via DC”, Elektrizitaetswirtschaft, Vol. 99 Issue 24, p. 83-5. 2000

[23] Hinrichsen, E.N., “Dynamics and stability of wind turbine generators”, IEEE Transactions on Power Apparatus and Systems, PAS-101, Issue 8, p. 2640-8. 1982

[24] E. Hirst and B. Kirby, “Costs for Electric Power Ancillary Services”, IEEE The Electric Journal, December issue, pp. 26-30, 1996

[25] IEC, “Wind Turbine Generator Systems Part 21: Measurement and assessment of Power Quality Characteristics of Grid Connected Wind Turbines”, Draft of IEC Standard 61400-21, 1st ed. Geneva, Switzerland, 2000

[26] IEC, “Adjustable Speed Electrical Power drive systems”, IEC-standard 61800-3, Geneva, Switzerland, 1996

[27] IEC, “Flickermeter – functional and design specifications”, IEC-standard 60868, Geneva, Switzerland, 1990

[28] S. Iniyan, L. Suganthi and T.R. Jagadeesan, “ Critical Analysis of Wind Farms for Sustainable Generation”, Solar Energy, Vol. 64, Issues 4-6, p. 141-9. 1998

[29] W. Isherwood, J.R. Smith, S.M. Aceves, G. Berry, W. Clark, R. Johnson, D. Deben Das Goering and R. Seifert, “Remote Power Systems with Advanced Storage Technologies for Alaskan Villages“, Energy., Vol. 25, No. 10 , p. 1005-20, 2000

[30] N. Jenkins, ”Engineering wind farms”, Power Engineering Journal, Vol. 7 Issue 2, p. 53 -60. 1993

[31] P. Jørgensen, J. O.Tande, A. Vikkelsø, P. Nørgård,J. S. Christensen, P. Sørensen, J. D. Kledal and L. Søndergård, “Power quality and grid connection of wind turbines”, CIRED. 14th International Conference and Exhibition on Electricity Distribution. Part 1: Contributions (Conf. Publ. No.438), Vol. 2, pp. 6/1-6, 1997

[32] A. Keyhani, A. Kian, J. Cruz and M. A. Simaan, “Market monitoring and control of ancillary services”, Decision Support Systems, Vol. 30, Elsevier, pp. 255-267, 2001

[33] H. Knudsen and V. Akhmatov, “Evaluation of Flicker in a T&D Network With a Large Amount of Dispersed Windmills”, Proceedings of the International Conference CIRED-2001, Paper 226, Amsterdam RAI, The Netherlands, 2001

[34] L. Landberg, A. Joensen, G. Giebel, H. Madsen and T. S. Nielsen, “Short-term prediction towards the 21st century”, Proceedings of the 1999 Twenty-First BWEA Wind Energy Conference WIND ENERGY Wind Power Comes of Age, pp. 371-6, 1999

[35] D. J. Lew, R. H. Williams, X. Shaoxiong and Z. Shihui, “Large-scale Baseload Wind Power in China”, Natural Resources Forum, Vol. 22, No. 3 , p. 165-184, 1998

[36] G. R. Mohapatra, A. Kalam, A. Zayegh and R. J. Coulter, “Dynamic Stability Analysis of Renewable Energy Sources Interconnected to the Distribution Network”, Procedings of the 3rd International Conference On Modelling and Simulation, pp. 327-30, 1997

[37] G. R. Mohapatra, A. Kalam, A. Zayegh and R. J. Coulter, “Voltage Stability Analysis of Renewable Energy Sources Interconnected to the Distribution Network”, Procedings of the 3rd International Conference On Modelling and Simulation, pp. 317-22, 1997

[38] M. Muchayri and M. E. El-Hawary, “A Summary of Algorithms in Reactive Power Pricing”, Electrical Power and Energy Systems, Vol. 21 Elsevier, pp.119-124, 1999

[39] R. Mukhedkar, T. Davies and H. Nouri, “Voltage Collapse: An Overview”, Proceedings of Universities Power Engineering Conference UPEC ‘99, Vol. 2, pp. 592-595, 1999

[40] A. S. Neris, N. A. Vovos and G. B. Giannakopoulos, “ A Variable Speed Wind Energy Conversion Scheme for Connection to Weak AC Systems”, IEEE Transactions on Energy Conversion, Vol. 14, No. 1, pp. 122-128, 1999

[41] M. Noroozian, L. Ängquist, M. Ghandhari and G. Andersson, “ Improving Power System Dynamics By Series-Connected FACTS Devices”, IEEE Transactions on Power Delivery, Vol. 12, No. 4 , pp. 1635 –1641, 1997

[42] J. C. Passerlergue, Y. Besanger, N. Hadjsaid and R. Feuillet, “Effects of FACTS Devices on Static Voltage Stability”, Proceedings of Universities Power Engineering Conference UPEC ’96, Vol. 3, pp. 945-948, 1996

[43] J. K. Pedersen, “Power Transmission from Large Offshore Wind Farms”, 34th Universities Power Engineering Conference, Vol. 2, pp. 369-72, 1999

[44] B. Rajsekhar, F. van Hulle and D. Gupta, “Influence of Weak Grids on Wind Turbines and Economics of Wind Power Plants in India”, Wind Engineering, Vol. 22, Issue 3, pp. 171-81, 1998

[45] N. S. Rau and M. Y. Wan, “Optimum Location of Ressources in Distributed Planning“,IEEE Transactions on Power Systems, Vol. 9 Issue 4, pp. 2014-2020, 1994

[46] J. O. G. Tande, ”Impact of Wind Turbines on Voltage Quality”, 8th International Conference On Harmonics and Quality of Power Proceedings, Vol. 2, pp. 1158 –1161, 1998

[47] J. O. G. Tande, ”Exploitation of Wind-energy Resources in Proximity to Weak Electric Grids”, Applied Energy, Vol. 65, Issue 1-4, pp. 395-401, 2000

[48] J.O.G.Tande and K.Uhlen, “Wind turbines in weak grids - constraints and solutions”, CI-RED. 16th International Conference and Exhibition on Electricity Distribution, 2001. Part 1: Contributions. (IEE Conf. Publ No. 482), Vol.4, pp. 94-98, 2001

[49] Y. Tang and A. P. S. Meliopoulos, “Power System Small Signal Stability Analysis with FACTS Elements”, IEEE Transactions on Power Delivery, Vol. 12, No. 3, pp. 1352-61, 1997

[50] A. Tapia, G. Tapia, X. Ostolaza, E. Fernándes and J. R. Saenz, “Modelling and Dynamic Regulation of a Wind Farm”, Proceedings of the IEEE CIEP conference, ISBN: 0-7803-6489-9,pp. 293-297 Mexico, 2000

[51] C. W. Taylor, “Power System Voltage Stability”, McGraw-Hill Companies Inc. ISBN: 0070631840, 1994

[52] T. Thiringer, “Integration of Large Sea-based Wind Parks – How Much Power Electronic Devices are Needed in Order to Avoid Power Quality Problems on the Grid?”, 2000 Power Engineering Society Summer Meeting (Cat. No.00CH37134), Vol. 2, pp. 1277-9, 2000

[53] K. S. Verma, S. N. Singh and H. O. Gupta, “FACTS Devices for Enhancement of Total Transfer Capability“, 2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.01CH37194), Vol.2, pp. 522-7, 2001

[54] M. E. Porter, “What is Strategy?”, Harvard Business Review, Nov.-Dec,1996, 79-91

[55] J. R. Montanari & J. S. Bracker, “The strategic management process at the public planning unit level”, Strategic Management Journal, Vol. 7, No.3, pp.251 - 265, 1986

[56] Asthana, K. J. Ostrowski & B. Venkateshwara, “Finding the balance of power”, McKinsey Quarterly, Q1, pp.82-91, 2001

[57] E. de Leyva & P.A. Lekander, “Climate change for Europe’s utilities”, McKinsey Quarterly, Q1, pp.120-131, 2003

[58] L. Birnbaum, J. M. del Aguila, G. D. Orive & P.A. Lekander, “Why electricity prices go haywire”, McKinsey Quarterly, Q1, pp. 64-72, 2001

[59] J. A. Colledge, J. Hicks, J. B. Robb & D. Wagle, “Power by the minute”, McKinsey Quarterly, Q1, pp.73-81, 2002

[60] H. Ansoff, “Corporate Strategy”, Penguin Press, New York, USA, 1988.

[61] M. E. Porter, “Competitive Advantage: Creating and Sustaining Superior Performance”, Free Press, New York, USA, 1985.

[62] M. E. Porter, “Competitive Strategy: Techniques for Analyzing Industries and Competitors”, Free Press, New York, USA, 1980.

[63] M. E. Porter, “The Competitive Advantage of Nations”, Free Press, New York, USA, 1990

[64] C. Bowmann & D. Faulkner, “The Essence of Competitive Strategy”, Prentice-Hall, New York, USA, 1995.

[65] M. H. J. Bollen, “Understanding power quality problems”, IEEE PRESS, New York, USA, 2000

[66] P. Kundur “Power System Stability and Control (The Epri Power System Engineering)”, McGraw-Hill Companies Inc., ISBN: 007035958X, 1994

[67] L. Sandholm, “Total Quality Management”, Studentlitteratur, Lund, Sweden, 2000

[68] A. H. Maslow, “A theory of human motivation”, Management and Motivation, Penguin Books, New York, USA, 1992

[69] L. Freris , “Wind Energy Conversion Systems”, Prentice Hall, New York, USA, 1990

[70] Å. Larsson, “The Power Quality of Wind Turbines”, PhD-thesis, Department of Electric power engineering, Chalmers University of Technology, Gothemburg, Sweden, 2000

[71] CIGRE, “Long Term dynamics phase II”, Technical report, CIGRE Taskforce 38.02.08, 1995

[72] P.A. Rosas, “Dynamic Influences of Wind Power in The Power System”, PhD-thesis, Ørsted-DTU, Technical University of Denmark, Kgs. Lyngby, Denmark, 2003

[73] J. Zhong, “Design of Ancillary Service Markets: Reactive Power and Frequency Regulation”, PhD-thesis, Department of Electric Power Engineering, Chalmers University of Technology, Gothemburg, Sweden, 2001

[74] European Committee for Electrotechnical Standardization, CENELEC, EN 50160, Voltage Characteristics of Electricity Supplied by Public Distribution Systems, 1994

[75] B. Peterson, “Induction Machine Speed Estimation – Observations on Observers”, PhD-thesis, Department of Industrial Electrical Engineering and Automation, Lund University, Lund, Sweden, 1996

[76] V.Ahkmatov and H. Knudsen, ”An aggregate model of grid-connected, large-scale offshore wind farm for power stability investigations – Importance of windmill mechanical system”, Eletrical Power and Energy Systems, vol. 24, no.9, pp.709-717

[77] P. Sørensen, A. Hansen and P. A. Rosas, ”Wind models for prediction of power fluctuations from wind farms”, Journal of Wind Engineering, n. 89, October, 2001

[78] K. Johnsen and B. Eliasson, “SIMULINK® Implementation of Wind Farm Model for use in Power System Studies”, Proceedings of Nordic Wind Power Conference ’04, Gothemburg, Sweden, 2004

[79] K. Johnsen, “Real-Time Simulation Studies of Large Scale Integration of Wind Power in Southern Sweden”, Proceedings of the IASTED EuroPES conference 2004, Paper no.442-172, Rhodes, Greece, 2004

[80] K. Johnsen, “Need for New Business Strategies for Driving Value in a Liberalised Electric Power Market”, Proceedings of the IASTED EuroPES conference 2004, Paper no.442-171, Rhodes, Greece, 2004

[81] K. Johnsen and B. Eliasson, “Real-Time Simulation Model of Wind Parks”, Proceedings of the IASTED EuroPES conference 2004, Paper no.442-288, Rhodes, Greece, 2004

[82] P.Sørensen, A.K. Unnikrishnan and S.A. Mathew, “Wind farms connected to weak grids in Dinda”, Wind Energy Vol. 4, pp.137-149, 2001

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APPENDIX A : BASIC POWER SYSTEM BEHAVIOUR

A.1. Overall features of power systems

A.1.1. Supply of electrical power and energy

Electricity is one of the most widespread commodities in society, mainly due to the flexibility of electric power and energy. To most people, supply of electricity is taken for granted – however, maintaining stable conditions in an electrical power system, and thereby maintaining supply, is a quite complex matter, due to the nature of electricity and electric power systems. The supply of electricity in an electric power system is the supply of a current, $\boldsymbol{I}$, at a voltage level, $\boldsymbol{E}$, both expressed as complex measures, according to the phase of the current and voltage signals, respectively. From this, the apparent power can be defined as

$$S = E \cdot I^{*} \tag{8}$$

where * indicates complex conjugation.

Most crucial in the understanding of electric power system is the acknowledgment of the difference between electric energy and electric power, because these two terms are often mistaken to be the same by laypersons. Apparent electric energy, $\boldsymbol{W_e}$,[15] can be regarded as the total amount of "work" that is taken out of the plug during a certain period of time, whereas apparent electrical power, $\boldsymbol{S}$,[16] is the speed or intensity of the "work" carried out. The relation between apparent electric energy and apparent electric power can be expressed as[17]

---

[15] Measured in MAVh, MWh or MVArh

[16] Measured in MVA, MW or MVAr

[17] In this case, the integral and differential operators should be interpreted as operators functioning on as real Riemann operators on the real an imaginary part respectively, i.e. as

$$W_e = \int S dt \quad \Leftrightarrow \quad S = \frac{dW_e}{dt} \tag{9}$$

Apparent electric energy is a measure of the »amount«, whereas power is a measure of »intensity«.

What is the actual benefit for the consumer is not only the total available amount of energy, but the possibility of drawing out electric power over a certain period of time – customers want to be able to draw out power over a period of time when they need it, not just when it is available. Thus, there are two means of measuring power supply and consumption:

- Supply/consumption of electric energy (i.e. a measure of supply/consumption of »amount«)
- Supply/consumption of electric power (i.e. a measure of supply/consumption of »capacity« or »intensity capability«)

Both the total amount of energy supplied and the intensity that it can be supplied with is of importance. When it comes to electric power systems, being able to supply the demanded electric energy is not enough, if the power supplied is not sufficient. So, when it comes to producing electric energy, the crucial factor is not to be able to provide the customers with the total amount of energy they need, but to be able to provide the customers with the total amount of power they need at all times.

It represents a total lack of understanding if an electric power system operator or distributor only focuses on being able to produce the amount of energy needed, if it is not ensured that the maximum consumption intensity of power needed to all times can be delivered simultaneously.

As commonly known, electric energy cannot be long term stored by the consumer; electric energy produced at 7 o'clock in the morning cannot be stored by the consumer until 7:30 that same day – at least not at a reasonable price. Electric energy has to be produced as it is consumed. Neither on system level are there many means of storing electric energy for later use. Proposed techniques

---

$W_e = \int S dt \equiv \int \Re\{S\}dt + j \cdot \int \Im\{S\}dt$ and $S = \frac{dW_e}{dt} \equiv \frac{d\Re\{W_e\}}{dt} + j \cdot \frac{d\Im\{W_e\}}{dt}$

exist for storing larger amounts of electric energy in terms of e.g. potential mechanical energy in hydro power plants or fly wheels, as electro magnetically stored energy in superconductors (SMES), or as chemically bound energy in either hydrogen-stores or batteries – but none has proven economically viable, as the losses are to high[18]. Thus, a general stability criterion for electric power systems is that the apparent electric power produced should equal the apparent electric power consumed (incl. apparent power losses), or

$$S_{prod} - S_{cons} = 0 \tag{10}$$

As a corollary it can be seen that if this stability criterion is fulfilled, the produced amount of apparent energy produced will then equal the total amount of apparent energy consumed

A.1.2. Active and reactive power

Electric power can be regarded consisting of two components: Active power and reactive power.

Active power, $\boldsymbol{P}$,[19] is so to speak the kind of power that is drawn out from the plug that makes the vacuum-cleaner run and makes the light bulb glow – the kind of power that the consumer benefits from.

Reactive power, Q,[20] on the other hand, is the kind of power needed in the distribution and transmission network components to build up the electromagnetic fields and is necessary to maintain a stable and sufficient voltage level. It can be regarded as the “physical payment” that nature demands for letting the customers take advantage of the electric power. Though most power companies do not bill their customers for this kind of power, it is needed, and is produced, with production costs, as well as the active power around the electric power system, and its transmission demand capacity just as the transmission of active power does. Mathematically, active and reactive power can be expressed as the real and imaginary part of the apparent electric power, respectively, i.e. as

---

[18] On ultra short term small amounts electric energy can be “stored”, as either increased motion of the generators with an undesired change in frequency as a consequence, or it can be accumulated as increased pressure in the boilers of the thermal power plans, which is also undesired, as higher pressure enlarge the risk of damaging explosions in the power plant

[19] Measured in MW

[20] Measured in MVAr

$$S = E \cdot I^* = P + jQ \quad \Rightarrow \quad \begin{cases} P = \Re\{S\} \\ Q = \Im\{S\} \end{cases} \tag{11}$$

Neither active or reactive power can be stored in a manner that is economically viable. Therefore, there exist a stability criterion for both active and reactive power similar to the one expressed in (3), which is

$$P_{prod} - P_{cons} = 0 \tag{12}$$

and

$$Q_{prod} - Q_{cons} = 0 \tag{13}$$

respectively, when losses of active and reactive power are considered included in the consumption.

Generally two factors make the attainment of these balances of active and reactive power complicated: the fluctuating power consumption of the customers and failures in the electric system (all the way from the entrance door of the power plant to the plug in the housing complex) – none of these are factors are directly controllable for the operating power engineers.

A.2. Power system stability

Attaining a stable electric power system is crucial to the consumers that are served through the system. Instability may lead to shortage of supply or malfunctioning, or eventually destruction, of connected equipment. In general power system stability concerns the attainment of voltage stability and synchronous stability, both on long and short term. An overview of what power system stability concerns is given in Fig. 16.

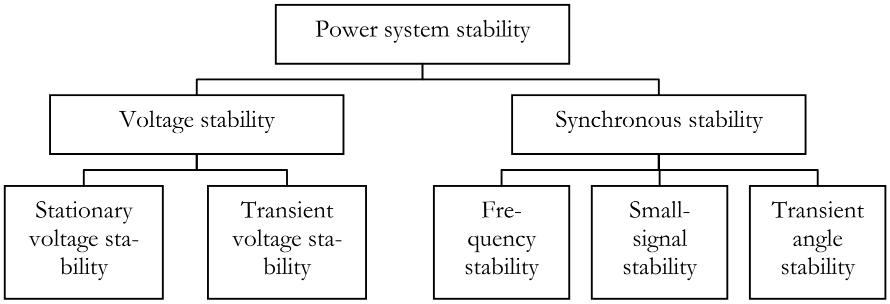

Fig. 16. Hierarchy of power system stability.

The details of voltage stability and synchronous stability are presented in Appendix B and Appendix C, respectively.

Voltage stability concerns the attainment of stationary voltage stability and transient stability. Stationary voltage stability concerns the electric power system's ability to attain an acceptable voltage level, i.e as close to the rated voltage level as possible, everywhere in the electric power system under all kinds of ordinary operations over longer term. Transient voltage stability concerns the electric power system's ability to attain an acceptable voltage level when sudden changes occur, e.g. short-circuits, switching, lightning etc.

Synchronous stability concerns the attainment of synchronism between the interconnected electrical machines in an electric power system, mainly. Frequency stability can be regarded as the electric power system's ability to attain a stable frequency close to the rated frequency of the system. Small-signal angle stability concerns the electric power system's ability to damp electromechanical power oscillations from smaller disturbances, like switching, oscillating power sources[21] or oscillating loads. Transient angle stability concerns the electric power system's ability to damp the electromechanical oscillations when larger disturbances occur, like faults or lightning.

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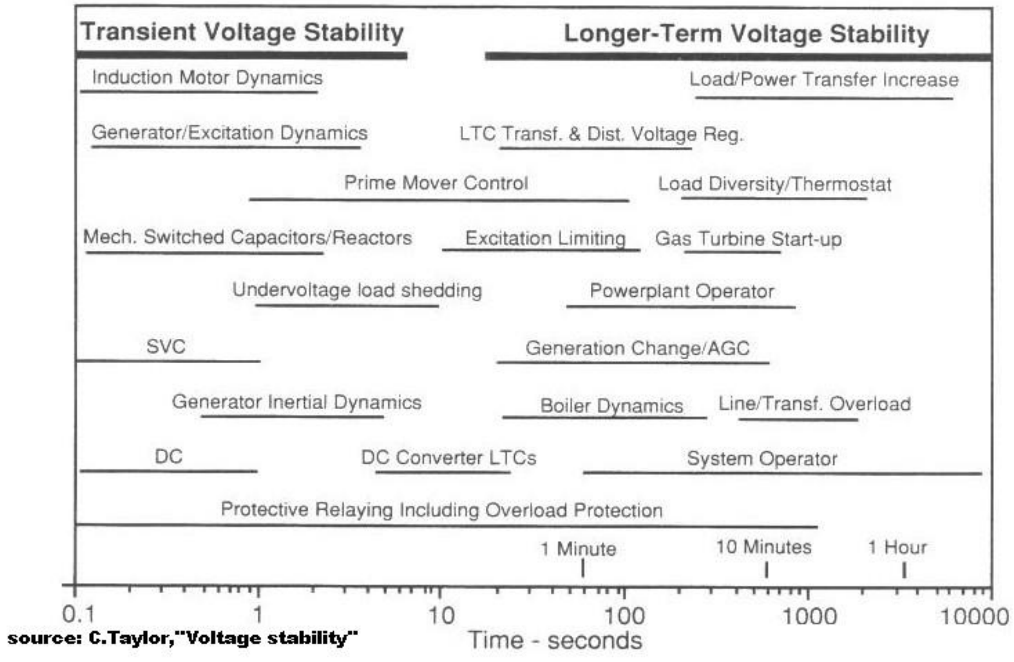
[21] In this thesis, *oscillating power sources* or *oscillating loads* is used for electrical power production units or loads, which are not constant over time but produces/consume a time-varying amount electric power, whereas *power oscillations* are used for the un-damped electromechanical oscillations between e.g. generators in an electric power system

APPENDIX B : ON VOLTAGE STABILITY

B.1. Stationary or transient voltage stability

It is not possible to exactly define a clear difference between stationary and transient voltage stability. Both stationary and transient voltage stability principally relies on the same physical properties, but the time-frame differs. Stationary voltage stability concerns voltage stability related to slower changes of the electric power system properties (changing over minutes or slower), whereas transient voltage stability concerns voltage stability from faster changes of the electric power system (changing over minutes or faster).



source: C.Taylor,"Voltage stability"

Fig. 17. Voltage stability timeframes. From [51].

The subject of stationary voltage concerns the attainment of a stable, acceptable voltage level under normal operations, such as slow increases/decreases in production or loads in various places of the electric power system.

Transient voltage stability principally concerns voltage stability under all kinds of unintentional operations. These unintentional operations may cause smaller disturbances, to which the small-signal voltage stability is related, or larger disturbances

B.2. Understanding power system and voltage stability

B.2.1. The simple transmission line approach

The voltage level of a electric power system may be affected if an electric power producing or electric power consuming component is connected. This is dependent on the change in apparent electric power that flows through this connection in the electric power system; the larger the change, the large the potential change.

From basic transmission line modeling, illustrated in Fig. 18, it is can be learned that there is a close coupling between the transmission of reactive power through a distinct line and the voltage-drop along the line.

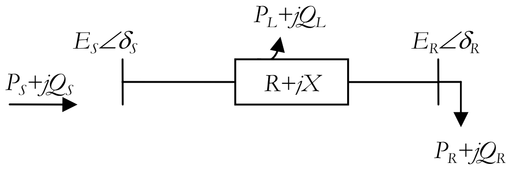


Fig. 18. Simple transmission line model; P is active power, Q is reactive power, R is the line resistance, X is the line reactance, E is the modulus (level) of the voltage, and δ is the argument (angle) of the voltage; indices S, R and L denote sending end, receiving end and loss, respectively.

The relations between voltages and power in both receiving and sending end can easily be calculated, using (1) and Ohms Law, as

$$\begin{aligned} S_R = P_R + jQ_R = \left(E_R \angle \delta_R\right) I^* &= E_R \left[\frac{E_S \, cos\overbrace{\left(\delta_S - \delta_R\right)}^{\delta} + jE_S \, sin\left(\delta_S - \delta_R\right) - E_R}{R + jX} \right]^* \\ &= \underbrace{\frac{E_R\left(E_S R \, cos(\delta) + E_S X \, sin(\delta) - E_R R\right)}{R^2 + X^2}}_{P_R} + j \underbrace{\frac{E_R\left(E_S X \, cos(\delta) - E_S R \, sin(\delta) - E_R X\right)}{R^2 + X^2}}_{Q_R} \end{aligned} \tag{14}$$

and similarly for the sending end. Usually transmission lines are designed to minimize the resistive value of the line impedance, i.e. it is reasonable to assume the ***R***<<***X***. Therefore the expressions for the active and reactive power becomes

$$\begin{aligned} P_R &\approx \frac{E_R E_S X \, sin(\delta)}{X^2} = \frac{E_R E_S \, sin(\delta)}{X} \propto sin(\delta) \approx \delta \\ Q_R &\approx \frac{E_R X \left(E_S \, cos(\delta) - E_R\right)}{X^2} = \frac{E_R\left(E_S \, cos(\delta) - E_R\right)}{X} \propto E_S \, cos(\delta) - E_R \approx E_S - E_R \end{aligned} \tag{15}$$

From this it can be seen that, for small values of δ, the active power goes with the phase angle of the voltage, and the reactive power goes with the difference in voltage levels over the line. Thus, if a large amount of reactive power is to be transmitted through a line, the voltage drop over the line must be equivalently large.

This balance, however simplified, applies on all the interconnected transmission lines in the power system, making the overall steady-state voltage profile heavily relying on the flow of reactive power in the system.

B.2.2. The π-equivalent approach

The simplified approach in section B.2.1 gives an idea of how voltage level, voltage phase angle and the flow of power are correlated. However, the transmission line model used is in many respects very simplified compared to the real life behavior of a transmission line, as it does not take into account the capacitive behavior of the line. Thus, the model from section B.2.1 should be extended with shunt capacitance along the line.

If instead a model, that regards the transmission line as built up of a continuum of infinitesimal transmission line fragments, consisting of a series reactance and series resistance with a shunt capacitance, one will have a model as shown in B.2.1. In this model a more true behavior of the line can be investigated.

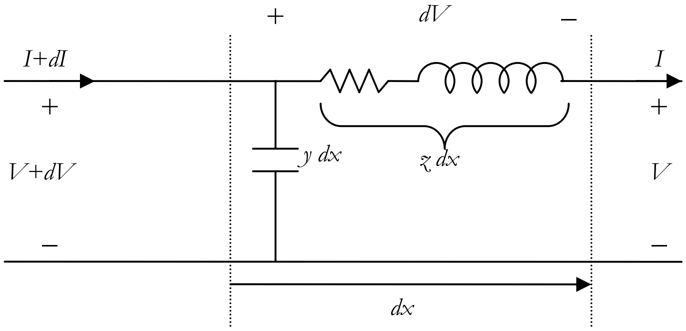


Fig. 19. Advanced π-equivalent model for the transmission line; the line consist of a continuum of infinitesimal transmission line units, where a series impedance, *z dx*, which is proportionate to differential of the length, with shunt capacitance, *y dx*, which is also proportionate to the differential of the length connected along the line. In the sending end, a transmitted current, *I*, is injected together with a capacitive load current, *dI*, for loading the capacitance of the line, at a voltage level of *V + dV*, where *dV* is the voltage drop along the transmission line. In the receiving end, a transmitted current of *I* at a voltage level *V*.

If an infinitesimal unit of the line, with the length ***dx*** is regarded, it will have a series impedance that is given as the length of the regarded line unit, ***dx***, multiplied with the relative impedance, ***z***, of the line, that is ***z dx*** in total; equivalently, the capacitance of the infinitesimal unit of the transmission line will be given as the product of the length of the line unit and the relative capacitance, ***y***. If Ohm's law is applied on both the series and the shunt connection it can be determined that the relation between voltages and currents of the transmission line becomes

$$\frac{dV}{dx} = I \cdot z \tag{16}$$

and

$$\frac{dI}{dx} = V \cdot y \tag{17}$$

where ***dV*** is the voltage drop along the infinitesimal transmission line unit when a current of ***I*** passes the series part of the line, and ***dI*** is the capacitance load current of the transmission line unit capacitance at the voltage level ***V***. From this it can be easily derived that

$$\frac{d^2 I}{dx^2} = I \cdot y \cdot z \qquad (18)$$

and

$$\frac{d^2 V}{dx^2} = V \cdot y \cdot z \qquad (19)$$

From these differential equations an expression for the voltage and the current in the sending end as function of the voltages and currents in the receiving end can be determined, for a given total length, ***l***, of the line, as

$$V_S = V_R \, cosh(\gamma \cdot l) + Z_C I_R \, sinh(\gamma \cdot l) \qquad (20)$$

and

$$I_S = I_R \, cosh(\gamma \cdot l) + \frac{V_R}{Z_C} sinh(\gamma \cdot l) \qquad (21)$$

where γ, the propagation constant of the line, and $\boldsymbol{Z_C}$, the characteristic impedance of the line, are defined as

$$\gamma = \sqrt{\frac{(R_l + j\omega L_l)\cdot(j\omega C_l)}{l^2}} = \sqrt{\frac{(R_l + jX_l)\cdot(jB_l)}{l^2}} \qquad (22)$$

and

$$Z_C = \sqrt{\frac{R_l + j\omega L_l}{j\omega C_l}} = \sqrt{\frac{R_l + jX_l}{jB_l}} \qquad (23)$$

respectively. Here, $\boldsymbol{V_R}$ and $\boldsymbol{V_S}$ are the receiving and sending end voltages, respectively, $\boldsymbol{I_R}$ and $\boldsymbol{I_S}$ are the receiving and sending end currents, respectively, $\boldsymbol{R_l}$ is the total line resistance, $\boldsymbol{L_l}$ is the total line inductance, $\boldsymbol{X_l}$ is the total line reactance at the angular frequency ω, $\boldsymbol{C_l}$ is the total line shunt capacity, and $\boldsymbol{B_l}$ the total line shunt admittance at the angular frequency ω.

B.2.3. Load or production impact on stationary voltage stability

In the task of attaining voltage stability, both the load behavior and the behavior of production generator units have an impact.

Regarding loads, the behavior of the load when exposed to voltage changes influence the stability by changing the load condition; dependent on the load characteristic, e.g. the active power consumption may decrease or increase over time when exposed to voltage drops, and/or the reactive power consumption may decrease or increase over time. As examples may e.g. be mentioned

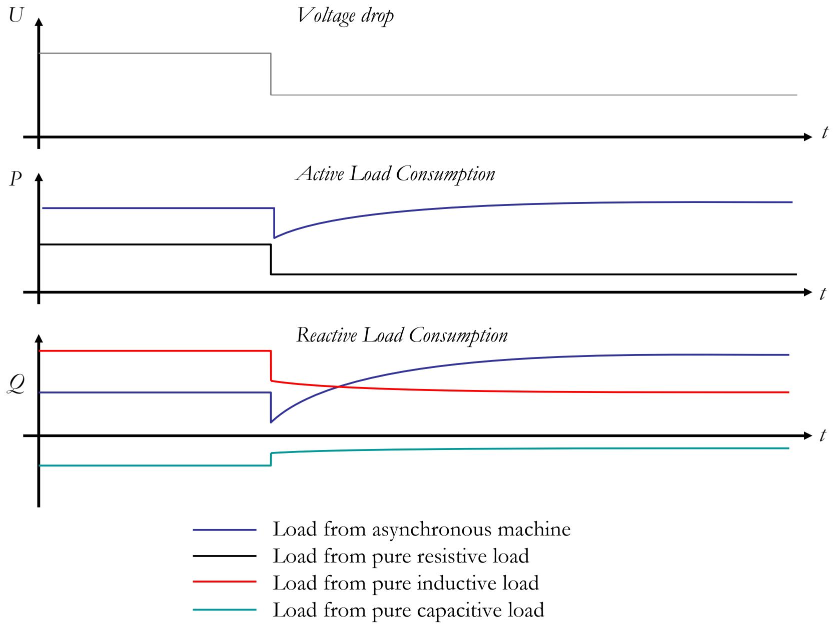


Fig. 20. Examples of different load consumption profiles.

- Pure resistive loads: Pure resistive loads simply immediately reduce or increase the load when a voltage drops or increases, respectively, to a static level.
- Loads with inductive/capacitive characteristics: Due to the nature of inductors and capacitors loads containing these have an immediate and a time-dependent size, when a voltage change occurs. Pure inductive loads react in an immediate voltage drop by an immediate drop in consumption of reactive power, followed by a exponential drop to a certain level. Capacitive loads behave dually.

- Asynchronous machines: When exposed to an immediate voltage drop, the active and reactive power consumption drops immediately, but changes over time. Dependent on the machine characteristics, the active power consumption firstly regains it pre-voltage drop magnitude, by drawing out an increased current, and may even increase according to the pre-voltage drop active power consumption level due to losses in the machine. Due to the increased currents in the machine, the reactive power consumption increases above the pre-voltage drop level

Other types of load may have different characteristics, such as thermostats or other electric regulation devices that may have an increase of load that is dependent of the time the voltage drop occurs.

Regarding the generator unit side, they also have an impact on how to attain voltage stability. Almost all generators are equipped with some kind of automatic voltage regulation system that mainly enables a regulation of the reactive power output from the generator, and hereby affects the voltage profile in the electric power system where it is connected.

Due to limitations in the physics of the generator unit, a generator may not make instant changes in power production. When it comes to reactive power, that is most important to voltage regulation, field winding of the generator as well as the armature windings limit both the amount of power that may be delivered and the rate that the output may be changed with.

To increase the level of reactive power output from a generator, the rotor field must be increased to increase the voltage induced in the field windings. Dependent on the load situation of the machine, there is a potentially a risk that the current in either the field winding or the armature winding may exceed what they may cope, if the automatic voltage regulation system does not take this risk in account. Thus, most automatic voltage regulation systems are equipped with both protection of the field and the armature windings; the field winding is protected by an over-excitation limiter, and the armature windings are protected by armature current limiters. These limiters can be said to set the outer limits for a generator units capability to support with reactive power for voltage control. Furthermore, the inductances in the generator set limits for how fast the reactive power output may be changed – but more important, the time constants in the automatic voltage regulation system determine the change rates, and these time constants are set according to characteristics in the rest of the electric power system (to avoid control modes)

B.2.4. Voltage collapse

Under some conditions it may occur that supply cannot serve the load in a bus or an entire area of an electric power system. Such conditions may evolve from e.g. faults in the system, in which some of the key parts of the electric power system (e.g. generation units, transmission lines,…) fall out of operation, and hereby leaves the system in a vulnerable state. When this occur, there is a risk that the electric power system in the area, where the load is larger than the supply capability, enters a state where attaining a stable voltage becomes impossible.

The reason why this can occur can be found in the properties of any transmission line. If regarded as a -line(as described in section B.2.2), the characteristic between voltage at the receiving end and the power drawn out in the receiving end becomes as shown in Fig. 21, showing the power/voltage characteristic (the so-called »nose-curve«) of a transmission line.

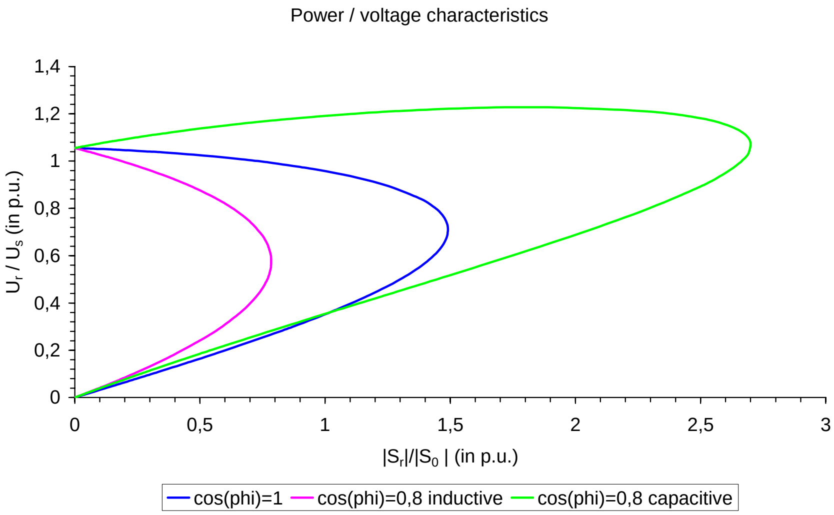


Fig. 21. Power/voltage –characteristic of a transmission line. Note the dependency of the characteristic on the load factor. Suffix r indicates receiving end, suffix s indicates sending end, and |S₀| is the characteristic power of the line.

The interpretation of this characteristic basically is that there is a reverse relationship between the loaded power in the receiving end and the resulting voltage in the receiving end – until a certain extent. The more MW and MVAr drawn out in the receiving end, the lower has the resulting voltage got to be, if the drawn out power is less than the maximum possible power transmitted by the line, i.e. less than the power at the »tip-of-the-nose-curve«, and the system operates on the upper-part of the characteristic. As long as the operation is on the uppermost part of the characteristic, this reverse relationship makes a kind of »negative feedback mechanism«, that makes the system stable. If the operation drives the system below the »tip« of the characteristic, this reverse relationship slips over to a direct relationship, making the system potentially unstable – the more the voltage is lowered, the less power can be transmitted.

In most cases when voltage collapses occur it is caused by a state of operation, that has driven transmission of power to a certain area below the »tip« of the characteristic, and the system has therefore operated in the lowermost part of the characteristic.

The specific characteristic of any part of an electric power system is much dependent on both the transmission capability between the regarded part of the system to the rest of the system and the actual load of the part regarded. The more lagging the load is, the relatively smaller will power transmission capability be (expressed in terms of the maximum possible power that may be transmitted – the »tip-of-the-nose-curve«) and vice versa. Thus, a large consumption of reactive power in an area limits the transmission capability to the area.

On the other hand, the more leading the load is, the relatively higher is the lowest allowable voltage level in the receiving end, if the system should not enter a state of potential voltage collapse. Thus, introducing shunt capacitors, as done when using passive capacitors for reactive power compensation, may increase the voltage locally, but also introduces a potential risk of voltage collapse at higher voltage levels.

APPENDIX C : ON SYNCHRONOUS STABILITY

C.1. Frequency stability

C.1.1. An electro-mechanical approach

In electric power systems, the revolving of the rotors in the generators that generate the electric power determines the frequency of the (fundamental) voltages and currents in the system. What causes the rotors to rotate in the first place is the mechanical power, which is employed on the shaft of the generator –this mechanical power comes from steam turbines, wind turbines or whatever the source of mechanical power might be. What the generator does is to transform the mechanical power from the mechanical power source into electric power that can ultimately be supplied to the consumers.

Initially a system that consists of a mechanical power source and a synchronous generator and a consumer can be shown as in Fig. 22.

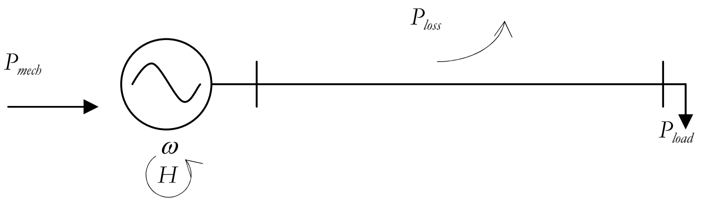


Fig. 22. Simple electric power system, with one generator and one load; mechanical power, P_{mech}, of some kind is introduced to the generator (on the rotor shaft, revolving with the angular frequency ω), which has an inertia constant of H, transforming it into electric power, that supplies the load, P_{load}, under the losses P_{loss}.

From basic mechanics, the rotational energy present in a rotating body is

$$W_{rot} = \frac{1}{2} H \omega^2 \tag{24}$$

where W_{rot} is the rotational energy, H is the inertia constant of the body and ω is the angular rotational frequency of the body. Thus, over a certain time period, in which the simple electric power system has been operating, the mechanical energy introduced on the rotor shaft of the generator must have been used for rotational energy, energy for losses and for loads, yielding

$$\begin{gathered} W_{mek} = W_{rot} + W_{e,loss} + W_{e,load} = \frac{1}{2} H\omega^2 + W_{e,loss} + W_{e,load} \\ \Updownarrow \\ \frac{1}{2} H\omega^2 = W_{mek} - \left(W_{e,loss} + W_{e,load}\right) \end{gathered} \tag{25}$$

where $\boldsymbol{W_{mek}}$ is the accumulated injected mechanical energy over the time period, $\boldsymbol{W_{e,load}}$ is the electrical energy dissipated in electric loads in the adjacent electric power system and $\boldsymbol{W_{e,loss}}$ is the dissipated energy in losses in the electric power system.

If differentiated with respect to time, energy becomes power, yielding the following power balance of the electric system in A.1

$$H\omega \frac{d\omega}{dt} = P_{mek} - \left(P_{e,loss} + P_{e,load}\right) \tag{26}$$

where $\boldsymbol{P_{mek}}$ is the injected mechanical power in the electric generator, $\boldsymbol{P_{e,load}}$ is the (electric) active power dissipated in electric loads in the adjacent electric power system and $\boldsymbol{P_{e,loss}}$ is the dissipated (electric) active power in losses in the electric power system. This links the balance of power (related to injected mechanical power and power losses and loads) in the electric power system closely together with the angular frequency of the rotor of the generator; thus, this links the balance of power together with changes in the fundamental frequency of the a.c.-voltages and currents in the electric power (system frequency).

In more complex electric power systems a similar expression can be set up, i.e. if there is number of generators and loads, the expression becomes

$$\sum_i\left(\omega_i\frac{d\omega_i}{dt}H_i\right)=\sum_j\left(P_{mek,j}\right)-\left(\sum P_{loss}+\sum_k P_{load,k}\right) \tag{27}$$

or if the frequency is the same in all machines in the system

$$\omega\frac{d\omega}{dt}\sum_i\left(H_i\right)=\sum_j\left(P_{mek,j}\right)-\left(\sum P_{loss}+\sum_k P_{load,k}\right) \tag{28}$$

C.2. Power oscillations

When connecting electric machines by an electric power system, they are connected in more than one sense. As described above, electric power systems with more than one machine can be described by equation (20), or simpler by (21) if the frequency is the same in all machines in the system. Problem by this last simplification is that it seldom occurs in a power system, that there are no differences in machines.

Just to illustrate this by one example, regard the case where one generating unit in a power system changes its production of active power will need the machine to change its pole angle (for the same reasons as for the transmission line in section B.2.1) - if the generator has to increase production, the pole angle has to increase and vice versa. Thus, some kind of acceleration or deceleration of the generator pole has to take place in order to change the active power production, and hereby slight changes in the frequency of the specific generator during operative changes. More prudent does these changes become when they are caused by transient occurrences in the electric power system, like couplings or faulty operations.

The fact that the machines are connected by an electric power system, actually »connects« the shafts of each generator together. A simple system of two machines in a power system would have to fulfill the following property

$$H_1\omega_1\frac{d\omega_1}{dt}+H_2\omega_2\frac{d\omega_2}{dt}=P_{mek,1}+P_{mek,2}-\left(P_{e,loss}+P_{e,load}\right) \tag{29}$$

In this case, the mechanical power on the shafts on the two machines are coupled through the electric power system, and thus the two generators are capable of exchanging the mechanical energy (i.e. mechanical power over time) between each other through the electric power system. When such an exchange takes place, one of the machines has to decelerate and one has to accelerate. But as they both are connected to the same electric power system, they at the same time tend to get a common system frequency, they swing back towards a common frequency value, and then exchange the energy once again – hence, the have started to oscillate towards each other, in a frequency dependent on the mechanical properties of the generators and the power system impedances. This leads to an oscillating flow of power in the electric power system, which is superimposed on the ordinary power flow in the system, caused by the loads and the corresponding production (load flow). These oscillations may, if un-damped, increase to amounts of energy, that result in either pole slipping or may occupy the entire transmission capacity of the electric power system. Both are harmful to the operation of the electric power system, and thus undesirable in an electric power system.

APPENDIX D : ON POWER QUALITY

D.1. Generally on power quality

D.1.1. Defining power quality

How to define power quality is a matter that is discussed widely, as there exist no formal definition of power quality that is accepted everywhere. However, there is an understanding of some of the aspects of electric power that are included in power quality

- Voltage stability – both transient and stationary
- Synchronous stability – both stationary, transient and small-signal stability
- Short-circuit power level
- Flicker
- Harmonics in voltages and currents
- Symmetry in load and generation
- Supply quality, both with respect to quantum and interruptions (intentional as well as unintentional) of the supply
- Safety - e.g. of the installations, to humans, animals and assets

These are all physical characteristics that may be measured and quantified, and they are as such objective qualities. Apart from these, other features of more subjective character can be specified, such as

- Quality in generation, i.e. related to the type of generation (e.g. generation from CHP's, wind turbines, coal plants or nuclear plants)

- Quality related to the generation site (bounded to e.g. national or regional placement of the generation)

More quality features of this kind can be set up.

All these aspects together forms what power quality is about, which may popularly be defined as all the features, apart from quantum, of electric power supply that add value for the consumer. This definition is quite wide in its nature, and might be considered to wide for technical evaluations, as this definition includes both the objective and the subjective quality attributes of the electric power.

In this appendix, only the objective quality attributes of electric power will be discussed for the sake of ease – not because the subjective ones does not matter, because these subjective aspects of power quality certainly do. An example of the importance of the quality in generation can be seen from the political decisions all over Scandinavia to increase the amount of wind generation, even though it would not directly be economically viable if it was not subject to substantial subsidies from the respective states. Politically it has been assessed that it is worth paying extra for wind generated electricity, compared to electricity from e.g. coal fueled plants.

Mapping and assessing these subjective power quality features is a complex cross-professional matter, which does not only include polytechnic disciplines, but also economic, sociologic and other humanistic and society related areas. This study is beyond the bounds of this study to investigate, however important

Thus, in this note, what is meant when discussing power quality is the ***technical*** features of electric power, apart from the quantum, that affect the added value of the supplied power for the consumer. In this note the aspects listed as the objective quality attributes of electric power are observed.

D.1.2. Why is power quality important?

The discussion of the importance of power quality is not a discussion that has been going on for ages, but a relatively recent one, as the focus on power quality on consumer level is relatively new. Though most of the different aspects of what is now considered as power quality have been regarded as isolated problems in earlier stages of the development of electric power systems. The perspective where these previously disjunctive problems are summed up in an overall assessment as ***power quality*** is only 10-15 years old.

Traditionally (and technically) there has been focus on the more fundamental aspects of power quality. Most fundamental, the attainment of supply (i.e. what could be regarded as supply quality) was the problem dealt with. Back in the old days, what the consumers wanted was just to be supplied with electricity, without jeopardizing their personal safety or the safety of their assets! With increased wealth, technological development and as people got used to having a supply of a certain level, they demanded some kind of voltage stability (making it possible to supply applications with electric power that were more sensible to variations in voltage), parallel with demanding that the supply became even more stable and that safety improved. And so on with demands of both new quality-related attributes of the electric power and the demands to the quality already supplied: demands for less harmonics in voltages and currents, voltage stability in all time frames (transient or stationary), quality in generation, etc. More wants more and more and better. Driven by the consumers wish to supply a larger number of more sensible and sophisticated applications with electric power, in order to supply themselves with increased wealth, resulting in even more demands, and so on.

Especially in the newer era of electric power supply, the demands have been driven by the application of new electric power consuming devices, such as electronics and especially optimized production facilities (e.g. computer systems, high-tech production lines using power electronics), that demands certain features about the delivered power to be able to operate at all. Further back in time, applications such as refrigerators and freezers dictated e.g. that interruptions should not be longer than 3-4 hours, and way back when the electric light bulb and the electric drive for trams and trains were the main power consumers, the supply of power should be more reliable and flexible than the "power supply" that could be provided from gaslights, horses and the newly invented combustion engine. Just having an electric installation that substituted some of the conventionally used technologies provided the consumer with a feeling of added value. Electric light felt safe and advanced, compared to light generated by open fire. Electric power applications in electric drives were flexible compared to horses, as it demanded less care and could be applied in places where horse-power cannot, and so on.

Seen from a historical and socio-economic point of view, this development in demand of power quality seems reasonable. From organizational theory, this behavior is usually described in the Maslowian hierarchy of needs, a theory proposed in the 1940'ies by the American psychologist Abraham Maslow. In short, this theory sees the demands, or needs, of any person as composed of a hierarchy of needs, beginning with basic needs and then advancing on to more "quality"-related needs. What is included in the distinct Maslow hierarchy for a person relies on the level of wealth, which the person has access to – the higher the general wealth of a person, the higher the demand of needs.

The development in demand of power quality can be seen from this point of view, as a hierarchy as the one shown in Fig. 23.

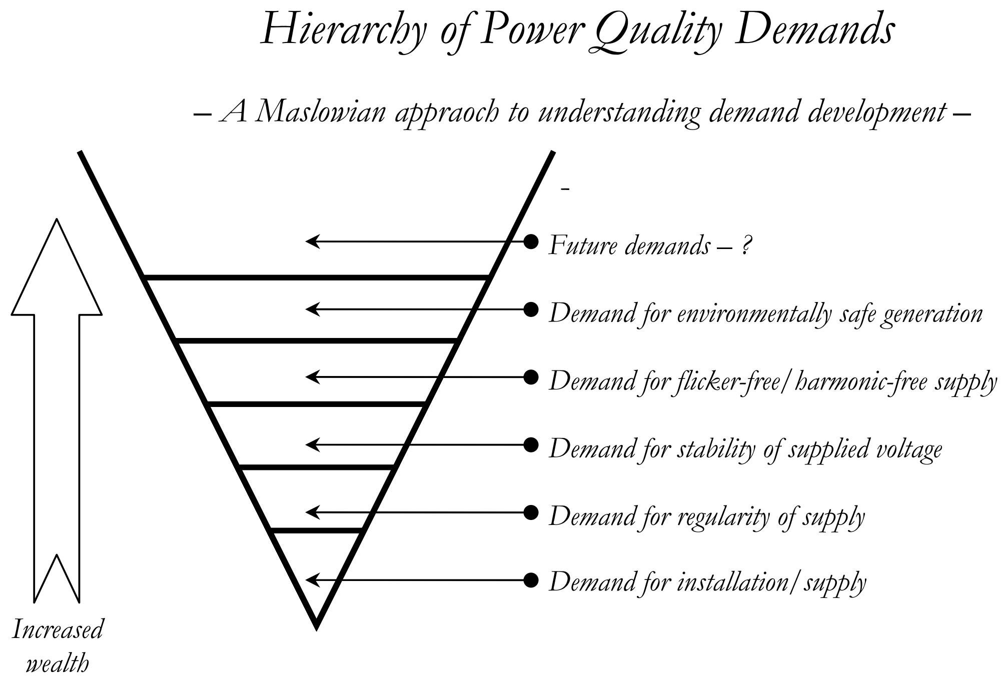


Fig. 23. Hierarchy of power quality demands from a Maslowian point of view; with increased wealth of the consumers, they will demand higher quality. (The list of demanded power quality attributes is not complete, but sketches the picture).

The higher the general wealth of the consumers, the higher the demand for quality to increase the sense of added value to the consumer. What is important to notice is that when the consumer rises from one level in the demand hierarchy to another, the demands expressed on the pervious level does not disappear, but remains, and are taken for granted, i.e. the levels in the demand hierarchy are cumulative, not exclusive. The fact that a consumer demands a flicker-free supply, does not mean that he becomes oblivious of the stability in the voltage supply.

Thus, the power suppliers face two problems: the demand not only for the supply of new kinds of qualities will keep on increasing, dependent on the development of the general consumer's wealth, but the demands of power qualities that are on lower levels in the demand hierarchy do not disappear. Once a demand is present, it is present for good. This means that the power business must prepare them selves to supply an ever increasing amount of power quality, spanning over more and more different power quality attributes.

In a liberalized power business, one way of succeeding in the market is to match the demands of the market at the relatively best price – hence, if the market demands a broader and more widespread supply of power quality, one way of obtaining success is to be able to supply a wide portfolio of power quality attributes at the best price. A certain way to self destruction is to neglect the demand. Power quality will become the prime value-driver in the electric power business, especially seen in the light of the restrictions that are set on the development in the turnover volume of the electric power delivered, which most governments try to limit, as increased power consumption is considered to be worse. In the Scandinavian region it is a normal obligation of the network operators on all levels to inform about how to save electric power consumption. Taking this into account, the way to growth in the electric power business does not rely on an increase in the turnover volume, but on an increase in delivered power quality attributes that drive value for the customer.

D.1.3. The nature of power quality

A central issue when it comes to power quality - knowing the reason why it is important to consider - is to uncover who is providing what to whom, and vice versa.

In an electric power system, the technical power quality attributes (i.e. level of harmonic distortions, fault level, balance of system etc.) originates from the physical electric power system. It is important to stress is that these attributes are affected by the interaction between load, network and generation. Technical power quality attributes go both ways, and is provided from both supply and demand, which is extraordinary[65]. Thus, power quality is not just flowing from the producer to the consumer, but also the other way around. It makes sense to consider both the power quality of the load and the power quality of the supply.

An example of this is harmonic distortions[65]: It is well known that dependent on the actual design of an electricity producing generator, a certain amount of harmonic currents and voltages are generated during the production of electric power. Hence, a generator provides a certain quality, related to the level of harmonic distortion in the power emitted onto the electric power system. On the other hand it is also known that certain designs of power electronic devices, connected as loads on the power system, emit harmonic voltages and currents to the electric power system, when drawing out electric power. Thus, making an overall assessment of the delivered power quality (related to harmonic distortions) in this case must include both the power quality in the load and the power quality in the generation. This applies for many technical power quality attributes, and must be considered.

D.2. Power quality assessment of wind turbines

In this appendix power quality is looked upon with regards to a broader definition than what is most common. The hierarchy of power quality can generally be shown as in Fig. 24.

As can be seen in Fig. 24, and as discussed in chapter 2, power quality can be subdivided into technical power quality features, which are usually measurable, quantitative and objective features, and non-technical features, which are usually qualitative and subjective features that are often hard to measure or survey. In the following, the technical features are the ones treated, well knowing that the non-technical features are evidently as important – and in some situations even more important than the technical ones.

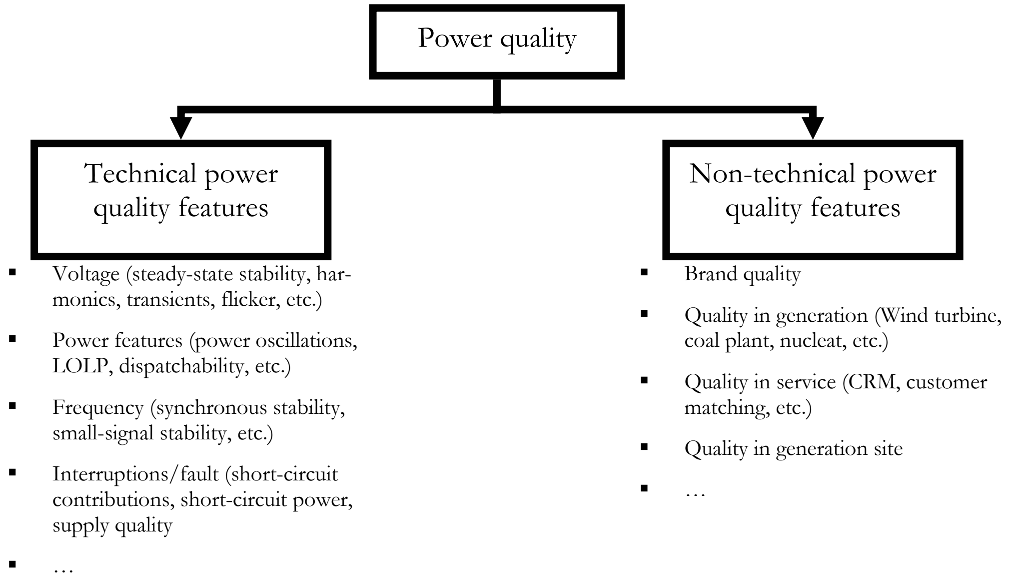


Fig. 24. An overview of power quality; classification of power quality features. Notable is that the technical power quality features are usually quantitative and objective features, and non-technical features are usually qualitative and subjective features.

Technical power quality can be defined as done in chapter 2. Often power quality is popularly defined as what is lacking from a power supply, that does not continuously supply a uniform sinusoidal voltage, containing only the rated fundamental frequency and the rated voltage of the system, that can supply an arbitrary amount of power at an arbitrary time – thus defining technical power quality by defining what it is not.

In the discussion below, some of the different aspects of power quality as discussed in relation to wind turbines. This discussion has, for the sake of ease, taken aspect for aspect as if they were independent of each other, even though the picture of power quality is much more complex. But it should be stated that almost all of the distinct aspects mentioned affect most of the others. Therefore, power quality assessment is only an assessment or a survey that indicates the level, but does not result in an indisputable result of what is the power quality of a certain device. It should be regarded as a whole, not as independent parts.

D.2.1. Wind turbine properties

It is a fact that wind turbines alter the level of power quality available in the electric power system, that they are connected to. Both positively and negatively – usually, technicians tend to focus on the negative effects that wind turbines may have on the technical power quality of the electric power system, but when evaluating the net power quality supplied a “balanced scorecard”, surveying the total power quality delivered (including also the non-technical features) by the wind turbines. The fact that the wind turbines alter the resulting operation power quality of the power system network supply can be regarded as the wind turbines supplying certain of power quality to the network.

To understand the mechanisms, that are the cause of the supplied power quality, it is necessary to know some of the basic properties of wind turbines. However, the walk-through of these properties will not be made in this note – a basic knowledge of the properties of wind turbine is assumed.

D.2.2. Quality of wind turbines related to voltage

D.2.2.1. Steady-state voltage quality of wind turbines

D.2.2.1.1. Wind turbine properties related to steady-state voltage stability

As applies for all other components connected to an electric power system, the power consumption of the component affects the properties of the network – this is of course also the case for wind turbines. When it comes to steady state voltage stability, wind turbines, dependent on type and equipment, are the most likely to affect it significantly, as most wind turbine generators tend to extract a vast amount of reactive power while producing active power. (A general reference for this section is [70]).

The common technology for wind turbine generators is asynchronous generators. The basic functionality of such a generator can be described by the network-representation in Fig. 25

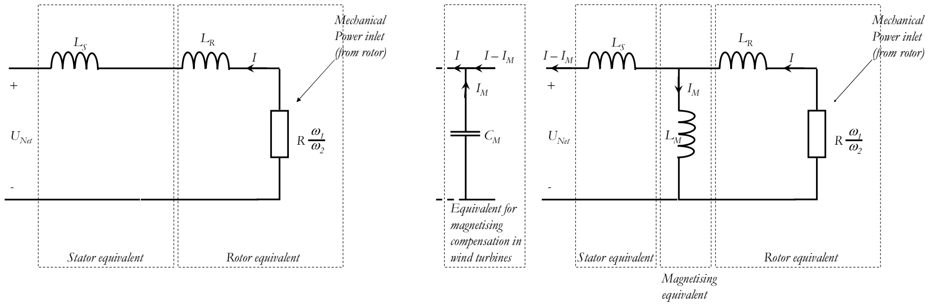


Fig. 25 Basic, loss-free equivalents for asynchronous generators, where ω_1 is the network angular frequency and ω_2 is the rotor angular frequency (electrically); (left) a basic equivalent for the asynchronous generator, with a rotor equivalent (index R designates "rotor"), a magnetizing equivalent (index M designates "magnetizing") and a stator equivalent (index S designates "stator"); the generated power, fed in from the wind turbine rotor, is modeled as the resistance R in the rotor equivalent, that injects power in the grid by generating a current that flows – i.e. the resistance is negative; in wind turbines it is common to try to compensate the reactive power consumption in L_M by externally connecting a capacitive load, C_M, that delivers the no-load consumption of reactive power to the asynchronous generator; (right) an even simpler equivalent of an asynchronous wind turbine generator, where it is assumed that C_M compensates L_M fully under all circumstances.

The reactive consumption due to the magnetizing equivalent is due to the magnetizing current I_M, that is either supplied by the electric power system (if no no-load compensation is applied to the asynchronous generator) or by the capacitive compensation (if applied).

In case such compensation is applied, a wind turbine equipped with an asynchronous generator as a system is neutral regarding the magnetizing reactive consumption – in such a system the magnetizing reactance may be looked apart from, but only as a rough approximation, as done in the equivalent circuit in the right of Fig. 25. Thus, the remaining reactive consumption of the wind turbine must be the stator and rotor consumption that is a consequence of the induced current in the rotor, due to the active power production.

Hence, if the apparent power output from a certain wind turbine to the net is calculated (from a 3 phase generator) becomes

$$S = 3 \cdot U_{Net} \cdot I_{ph}^{*}$$

yielding that the active power from a full wind turbine system (incl. capacitive compensation) production becomes

$$P_W = 3\Re\{U_{Net} \cdot I_{ph}{}^{*}\} = \underbrace{-3 \cdot \left|I_{ph}\right|^2 \cdot \underbrace{R \cdot \frac{\omega_1}{\omega_2}}_{Negative}}_{Positive} \propto \left|I_{ph}\right|^2$$

using the notation of Fig. 25. It should be stressed that ***R*** is negative, and the minus is due to the definition of the direction of ***I***. Not surprisingly, the active power is proportionate to the square of the equally, the reactive power from the full wind turbine system (incl. capacitive compensation) can be calculated as

$$\begin{aligned} & Q_W = 3 \cdot \Im\{U_{Net} \cdot I_{ph}{}^{*}\} = -3 \cdot \left|I_{ph}\right|^2 \cdot \underbrace{\omega_1 \cdot \left(L_S + L_R\right)}_{Positive} \propto -\left|I_{ph}\right|^2 \\ & \Updownarrow \\ & Q_W \propto -P_W \end{aligned}$$

i.e. the reactive power consumption can be assumed to be proportionate to the active power production of a wind turbine equipped with an asynchronous generator.

The important point about generation with asynchronous generators is that while producing active power, the generator consumes reactive power, that has to be supplied to the asynchronous generator from the net, and as discussed in sect. 3.2.1.1, the supply of reactive power through a transmission line is closely linked to the voltage level drop over the line. As a result of this, the logical conclusion must be that wind turbines equipped with asynchronous generators evidently lower the overall voltage level while producing, if they are not equipped with compensation that deals with the production consumption of reactive power. Therefore wind turbines equipped with asynchronous generators affect the power quality related to the steady-state voltage stability.

D.2.2.1.2. Assessing the power quality of wind turbines related to steady-state voltage stability

In general, the one of the purposes of an electric power system network is to be able to supply electric power (active or reactive) to components connected to it. It may therefore seem odd to regard the consumption of power – or reversely, the production of it – as a factor, that affects the overall power quality.

However, the predictability (or controllability) of the consumption (or the production) of power is of high importance, as the power flow in the network highly affects the steady-state voltage stability, as well as other power quality features. Thus, if consumption (or production) is fully predictable (or controllable) the planning/control of power flows in the electric power system becomes easier, and therefore the operation towards a high quality supply becomes easier. The more variability (or randomness) in the consumption (or production), the harder the planning, and the harder the operation towards supply with perfect power quality. Dependent on the skills of the system operator, high variations in consumption (or production) will more likely lead to a lower overall power quality in the supplied power e.g. when it comes to steady-state voltage stability.

As voltage-levels in the electric power system are so dependent on the actual transmission of active and (especially) reactive power in the electric power system, a fair assessment of the steady-state voltage quality of a certain component can be a scale, reflecting the long-term changes in the load or production of the distinct component. For a wind turbine, this means the long-term changes of its active and reactive power production, and accordingly for a wind farm. Dependent on the time-frame considered, a way of quantifying this is to record the changes over time of the production of power in a wind farm, and to calculate a variance estimate, using the following formulas

$$\Delta P_{t,\Sigma} = \frac{\sqrt{\sum_{i=1}^{N_{wt}} \left(P_{t,i} - P_{n,i}\right)^2}}{\sum_{i=1}^{N_{wt}} P_{n,i}}$$

$$\Delta Q_{t,\Sigma} = \frac{\sqrt{\sum_{i=1}^{N_{wt}} \left(Q_{t,i} - Q_{n,i}\right)^2}}{\sum_{i=1}^{N_{wt}} Q_{n,i}}$$

where P and Q refers to the active and reactive power, respectively, index t denotes the time-frame over which the variations are observed, summed up over a certain set of measurements/simulations carried out on a wind farm consisting of N_{wt} wind turbines with respective mean productions of active and reactive power of P_n and Q_n respectively. The mean is the mean value of the active/reactive power production, which is produced and hopefully could be forecasted in the production schedule in the period, where the assessment is performed – i.e. what could be expected to be produced at the distinct time. These formulas which are a reformulation of the way of assessing given in the IEC standard IEC 61400-21[25], principally apply for all time-frames where the production of the wind turbines in the wind farm (and the variation of it)is uncorrelated, may be desired to observe. When it comes to assessing the overall steady-state voltage quality it may be reasonable to consider time-frames of approximately 60 seconds or more (dependent on appliance) – i.e. a reasonable measure for steady-state may be t = 60s.

Assessing the impact on the steady-state voltage variation that the power production may have, principally it relies on both the active and the reactive power production. But as discussed earlier in section 3.2.1.1., the reactive power flow and the voltage are closely linked (closer than the active power flow and the voltage is), demonstrating that the measure of most importance is of course the one that assesses the reactive power flows.

These formulas do not take the dispatchability into account, even though it could be argued to be of importance – only does it account for the unpredictable production variations. On the other hand, dispatchability can be regarded as a more or less independent, and therefore this is treated later on.

This assessment may give an idea of how a component will react when it is connected to a power system, given its characteristics.

It may be argued that a major back-draft of this measure is that it does not give an indisputable measure of the exact impact on the system. Therefore this measure alone does not provide an exact indication of the resulting voltage quality of the net near the component. As the resulting voltage quality results from the interaction of (operation of) the electric power system network and the network properties, and the component, as well as the component’s interaction with other components in the electric power network, a measure like the above given cannot regardless be directly translated to the resulting voltage at the consumer, as such a measure does not include the steady state voltage quality obtained by proper network designs and operations.

However, if focus is aimed at the steady-state voltage quality delivered to the electric power system (regarding the power system as the “consumer”) and not the steady-state voltage quality delivered to the end consumer, it may reasonably be said that such a variance measure as given above provides information regarding the steady-state voltage quality delivered to the network from the component purely, as it does not regard the operations (which can be regarded as an enhancement of the power delivered) made by the system operator. Dependent on which point of view is adapted, variance estimates of the active and reactive power supply/consumption can be regarded as more or less adequate for describing the voltage quality of the given component.

When it comes to wind turbines, the variations in active power production and reactive power consumption are not negligible, especially not the long-period variations when a large number of wind turbines are connected at a certain location. To cope with these variations, the transmission network has to be designed to be able to compensate for these variations, i.e. to be able to supply or transmit a wide range of power according to the current need. Often, a way of coping with this is to strengthen the network, in order to make it possible simply to transmit larger quantities of power through or by locally putting compensation gear. This of course implies a resulting cost, that can give a primitive estimate of the value of the voltage quality supplied. If perfect voltage quality was supplied, only a minimum of gear would be necessary in order to transmit the power from wind turbine to consumer. As this is not the case, resulting in a need for compensation, for which the cost (running costs, investment costs as well as opportunity costs related to the compensation can be assessed, and therefore a first primitive evaluation of the cost of voltage quality can be made. This is the first step towards an actual pricing, lacking only the demand side of the voltage quality aspect when assessing the value of the power quality. This, however is not considered in this appendix.

D.2.2.2. Voltage fluctuation quality of wind turbines – flicker

D.2.2.2.1. On Flicker

Fluctuations in voltage that are faster than steady-state variations (but still not transient in their nature) are usually categorized as flicker, which originally refers to the flickering in the light emitted from a regular bulb during these faster variations. Flicker is a rather well-known phenomena, which has been regarded for quite a while, and is e.g. treated in the IEC standard IEC 60868[27]

Flicker is the phenomena of more or less uncorrelated a.c.-voltages of different frequencies that cause flickering light in light bulbs, and IEC 60868 set up boundaries for how much content of different voltage signals of different frequencies are allowed, as shown in Fig. 26.These maximum limits for the voltage signal content of different frequencies are defined from the human response to the luminance variations caused by voltage fluctuations in a 60 W light bulb.

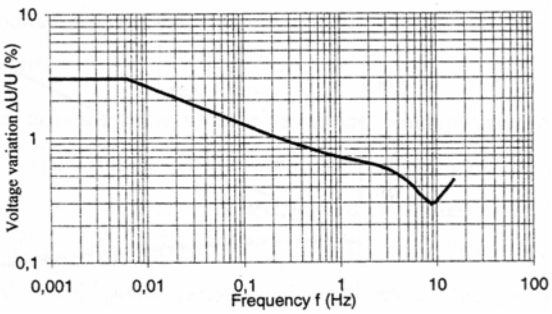


Fig. 26. Flicker curve, showing tolerances of voltage variation levels of different frequencies. From [70] and [27]

The contribution that a certain component gives to the flicker in the network is determined by its production of active and (mostly) reactive power production (or consumption which may be regarded as negative production).

When it comes to assessing the flicker contribution from wind turbines, the matter has been regarded in several studies, and in IEC 61400-21[25], the evaluation of the flicker emitted from wind turbines fall in two distinct cases: continuous operation flicker contributions and flicker contributions from switching.

D.2.2.2.2. Flicker contribution from continuous operation of wind turbines

When wind turbines operate, their fluctuations in production cause flicker, as the power emission from the wind turbines are not constant, as discussed in section 3.2.1. Thus, during operation the oscillating power emission from the wind turbine can be regarded as the reason for the flicker emitted from a wind turbine during continuous operation[70]. These oscillations may be caused by mechanical oscillations caused by the mechanical structure of the wind turbine (e.g. tower shadowing), or by turbulent behavior in the wind, that drives the wind turbines. Dependent on design of the wind turbine, and dependent on how the wind turbine is equipped with either internal control devices (e.g. pitch-control) or external devices (e.g. compensation gear, that can control the reactive power flow), these oscillations may be limited, yielding a higher voltage quality with respect to voltage fluctuations.

If the desire is to assess to which extent a wind turbine system emits flicker into the electric power system network that the wind turbine is connected to, again, the fluctuations in power (both active and reactive power) may seem a fair measure, as is the case for the steady-state voltage variations. Though, flicker oscillations in power may be summed together by the flicker curve that may be regarded as a weighting function, that weights the sensibility, which humans have to flicker. According to 3.2.1.1. it may be assumed reasonable in a first approximation to regard fluctuations in voltages as consequence of fluctuations in power productions – and as power is the product of voltages and currents, voltage and current signals of the same frequency result in a power fluctuation of twice the frequency. Thus, there is a link between the frequencies of the power oscillations and the frequencies of the resulting voltage fluctuation in the network, i.e. a link between the power fluctuation and the flicker.

Though, flicker assessment with regards to wind turbines during continuous operation makes only sense if the power production fluctuations reveal itself in voltage fluctuations. This can only be the case, if one evaluates the flicker from an actual connection to an electric power system. However, the manifestation of power production fluctuations as voltage fluctuations are highly dependent on the nature of the electric power system and other components connected to it – thus, voltage fluctuations occur as a consequence of the interaction between electric power system and component. Therefore a method for assessing flicker contribution from e.g. a wind turbine must be carried out in a manner that makes it possible to disregard the contributions from the electric power system, or at least standardize the assessment method and hereby making the network interaction the same to all. That is what is done in the standard IEC 61400-21.

This standard proposes that flicker contributions from wind turbines are assessed by the flicker coefficient, $c(\psi_k)$, a measure, which is highly dependent on the properties of the electric power system, to which the wind turbine is connected[70]. Therefore, in order to make the network contribution even for all kinds of wind turbines, what is regarded is a wind turbine connected to a fictitious electric power system, with a electric power system-angle defined as

$$\psi_k = tan^{-1}\left(\frac{X_k}{R_k}\right)$$

where X_k and R_k are the reactance and the resistance of the fictitious electric power system, respectively, and with a short-circuit power of, say, $S_{k,fic}$. If the wind turbine has a rated power of S_r, The flicker coefficient can be determined as

$$c(\psi_k) = P_{st,fic} \frac{S_{k,fic}}{S_r}$$

with $P_{st,fic}$ being the flicker emission level calculated in this fictitious network[70]. When determined, the flicker coefficient can then be used to evaluate the actual flicker contribution in a distinct network with a distinct short-circuit power S_k and network angle ψ_k by using that

$$P_{st} = c(\psi_k) \frac{S_r}{S_k}$$

As described in IEC 61400-21 for a wind farm, consisting of a number of wind turbines, it is fair to assess the flicker contribution of the full wind farm as the root-sum-square of the individual flicker contributions of each wind turbines, yielding a measure of

$$P_{st\Sigma} = \sqrt{\sum_i P_{si,i}^2} = \sqrt{\sum_i (c_i(\psi_{k,i}))^2 \left(\frac{S_{r,i}}{S_k}\right)^2} \propto \sqrt{\sum_i (c_i(\psi_{k,i}))^2}$$

Thus, a fair measure for the flicker contribution from a single wind turbine is the flicker coefficient of the wind turbine, and for a wind farm the root-square-sum of the flicker coefficients.

D.2.2.2.3. Flicker contribution from switching operations of wind turbines

When wind turbines are switched on or off, it creates, as it is the case for other components in an electric power network, first a short-term oscillation in the produced power and second a permanent change in the produced power. This of course alters the voltage level in the electric power network; the first oscillations lead to an oscillation in voltage whereas the lattermost leads to a long-term steady-state change in voltage level (the type given in section 3.2.1).

Though it is of importance to consider (and minimize) the flicker originating switching operations, it may be argued whether the switching operation related voltage fluctuations (including flicker) are at all the concern of the wind turbine, as switching is in fact part of the operation. It may therefore seem reasonable to regard switching operation voltage fluctuations and flicker as the problem of the operator only, and not a problem caused by the wind turbine. However, wind turbines in their start-up sequences is usually a significant contributor of switching operation flicker, often more than other components do during when they start, resulting in harder operation – though it depends on the actual wind turbine.

Furthermore, and even more critical, most wind turbines have a threshold wind speed where they go from not producing to producing power, and reverse. Hence, during periods where the wind speed is around this threshold-value, turbulent gusts in the wind can make the wind turbine start and stop several times over a small period of time, resulting in constant switching operations. This of course leads to an increased amount of voltage fluctuations, due to the continuously switching in and out.

Therefore, if one adapts a “rather-safe-than-sorry”-point of view, it makes even more sense to include the switching operation voltage fluctuations in a voltage quality assessment of a wind turbine.

Switching operation flicker is quantified in a similar way to the flicker at continuous operation, i.e. by connecting the wind turbine to a fictitious network with a short-circuit power of S_k and network angle ψ_k, and then calculating a voltage change factor, $k(\psi_k)$, as

$$k(\psi_k) = \Delta U_{k,max} \frac{S_k}{S_r}$$

where S_r is the rated apparent power of the wind turbine.

A special voltage change factor for wind turbines, defined in the standard IEC 61400-21, is the flicker step factor, $k_f(\psi_k)$, which is the voltage change factor calculated when the wind turbine is cut-in. This is probably the most adequate measure for the switching operations flicker, that a wind turbine contributes with, as it does only take into account the cut-in of the wind turbine generator, and does not reflect, what happens during all other kinds of switching. Therefore, a fair assessment of the switching operation flicker contribution of a wind turbine is the flicker step factor.

If a wind turbine happens to be affected by wind conditions, where it is continuously stopped and started, the flicker emission from this operation can, according to IEC 61400-21, be assessed by applying

$$P_{so} = 8 \cdot k_f\left(\psi_k\right) \cdot N^{\frac{1}{3.2}} \cdot \frac{S_r}{S_k}$$

and if the switching operation flicker of a wind farm is desired to be evaluated, it can be done by applying

$$P_{so\Sigma} = \sqrt{\sum_i P_{so,i}^2}$$

Closely related to the flicker that occurs during switching operations is the transients that originate from the switching. Transient voltages may cause malfunction to sensitive equipment, and may even result in increased component stress, reduced life time of connected components and ultimately destruction, if large enough. This can be regarded as a consequence of the operations in the network also, but when regarding wind turbine systems the network operations may require switching of e.g. capacitor banks or compensation gear, that otherwise would not be needed to operate. The transient voltage fluctuations from such switching operations may be significant, and therefore precautions must be made towards this, requiring an effort (and hereby inconvenience, i.e. a loss of power quality) from the operator. However, the impact of the wind turbines causing transient voltages due to switching operations must be evaluated from time to time, and dependent on the actual configuration of compensation gear and the characteristics of the electric power network, it may vary much from case to case. Therefore, the evaluation of the power quality supplied from the wind turbine may be hard to adequately assess.

D.2.2.3. Quality related to voltage harmonics

Harmonic and inter-harmonics voltages refers to certain voltage fluctuations of distinct frequencies, namely voltages with frequencies that are a multiple of the fundamental supply frequency (harmonic voltages – e.g. 100 Hz, 150 Hz, etc.) or a multiplicity plus the half of the fundamental supply frequency (inter-harmonics – e.g. 75 Hz, 125 Hz, etc.). Such voltage fluctuations may be hazardous to components in the electric power system, some more than others, resulting in emission of harmonic and inter-harmonic voltages result in lowered power quality. This applies for harmonic and inter-harmonic currents, also. It should be noticed that voltage harmonics and current harmonics usually go hand in hand. What causes the damage is the power that the harmonic voltages and currents produce.

As discussed in the standard IEC 61400-21, most wind turbines are equipped with asynchronous generators, which do not emit large amounts of harmonic or inter-harmonic voltages and currents. However, compensation equipment based on power electronics may contribute to a high amount of harmonics and inter-harmonic currents and voltages.

When it comes to assessing the number of harmonics, one must be aware that harmonics and inter-harmonics are present in the electric power systems everywhere – if the harmonic distortion that originates from a specific wind turbine or wind farm should be assessed, this “background-harmonic” distortion must be discounted. Thus, harmonic and inter-harmonic distortion contribution can be quantified using the total harmonic distortion index (THD), where the content of harmonics is cumulated up and set in relation to the content of the fundamental component regarded over a distinct period of time – usually the harmonic content is measured during 95% of a week based on 10 min. average measurements[22]. Various publications treat harmonics, and the standard IEC 61800-3[27] recommends that the THD of a network is in general lower than 5%, En 50160[74] recommends 8% - this, however does not say anything about the different components should behave. It only gives recommendations about how the entire system should. In general though it must be stated, that the lower the THD of a component is, the better the supply of voltage quality with regards to harmonics alone.

It may though be the case that some electric power systems are more vulnerable to certain harmonics or inter-harmonics. For that sake, quantification that weights the different harmonic components differently may be relevant – say, a similar index, a weighted harmonic distortion (WHD), is made instead. These indices may vary from one electric power system network to another, making such quantifications somewhat incomparable, but still, it must be expected that such indices in some cases reflect the relevant situation better than an overall THD. This weighting can also be accounted for by specifying the limits where under the harmonic distortion must be. A recommendation for

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[22] As defined in the European standard EN 50160

this is given below in Fig. 27, showing the recommended limits of different harmonics according to EN 50160.

Order (of harmonic)	Relative voltage content
3	5%
5	6%
7	5%
9	1,5%
11	3,5%
13	3%
15	0,5%
17	2%
19	1,5%
21	0,5%
23	1,5%
25	1,5%

Fig. 27. Recommended limits of harmonic voltage content, according to EN 50160

D.2.3. Quality related to the power output and frequency stability of wind turbines

In the beginning of what could be called “the wind turbine era” the amounts of wind turbine power introduced in the electric power systems were not significant, producing only a small amount of power compared to the total turnover of the whole system. Introduced on a small scale only, wind power does not for real represent any changes in the operation or the interfacing of the electric power system. But as the amount of wind turbine driven power production increases, with the introduction of massive wind farms with larger rated wind turbines, the impact on the operation becomes more relevant to regard. The higher wind turbine concentration, the more essential this issue becomes.

These problems fall into different categories, and are (as all other power quality related features) not confined to a single category.

D.2.3.1. Quality of wind turbines related to Frequency stability

D.2.3.1.1. On frequency stability

Attaining a stable frequency is of importance to the electric power system operators, and therefore this topic has been treated previous work. In the European standard EN 50160 it is recommended that the system frequency should be held at 50 Hz ± 2% under normal conditions, measured as 10 sec. average values. Further, it recommends that the frequency is held within this range during 95% of the time, measured over a week, and that the frequency is kept within the range 50 Hz ± 15% at all times.

From the power balances given in section C.1.1 two main conclusions can be drawn.

a. ***Mismatching load and production leads to changes in system frequency.*** From the equations in 3.3.2.1. it can be learned, that if there mechanical power introduced on the rotor shaft of the generator is larger than the loads and losses of the electric power systems, the higher the amount of power allocated for rotational energy, resulting in a higher angular frequency. The faster the angular frequency rise of the rotor, the faster a rise in system frequency. This is rather important to note, as it stresses the point that production and losses and loads ideally should be matched at all times – thus, having an undispatchable power source (i.e. a power source or generator whose production cannot be controlled) makes it hard to maintain a stable frequency. In addition having stochastic loads makes it hard too. When it comes to the loads, most loads are to be considered more or less stochastic in their nature, due to the different consumption patterns of each consumer – though, there are some tendencies, which are used in the production planning. Much effort is put in mapping consumption patterns using statistics as well as much effort is put in trying to make consumption more controllable/predictable e.g. through tariffing that benefits consumers for using power at certain times of the day, but still the consumption is stochastic in its nature, making the attainment of the balance complicated. The only way of really making consumption dispatchable is to shed loads in periods where the load exceeds the production, which is a most unfortunate way of attaining power balance. Making the picture even more mottled, electric power sources such as wind turbines, solar cells and even combined heat/power plants on distributed level (CHP's) are also more or less stochastic in their nature – at least, they are not necessarily very dispatchable, making it even more hard to attain frequency stability. Thus, the more dispatchable a power source is and the faster it can be regulated up or down, the better a power quality the power source supplies with respect to frequency stability.

b. ***The larger the (sum of the) inertia constant(s), the smaller the deviations in frequency.*** It can be directly seen from the equations of section C.1.1. that for a given unbalance of power, the rotation energy of the generators functions as a short term “power buffer”, compensating immediately for the unbalance in power with a rise or decline in frequency. Hence, the larger the inertia constants in the respective generators, the less changes in frequency are needed to compensate for a given unbalance of power in the electric power system. If an electric power system has a large cumulated inertia constant of its generators, the better can the system cope with changes in the power balance. Thus, the more a power source contributes to the cumulated inertia constant, the better the power quality of the source with respect to frequency stability.

Quantification of a wind turbine’s ability to attain and support frequency stability hence must concentrate around the wind turbine dispatchability (which is treated later on) and its contribution to the common cumulated inertia constant of the electric power system, to which it is connected.

The importance of the quality related to frequency stability of all kinds of dispersed generation (including wind power) is especially important when regarding systems that (due to some reasons) risk to be split in islands. Under such conditions, each island will in fact operate as in independent, autonomous electric power systems, for which the power balance has to be maintained. If a larger electric power system falls into islands, the operation with respect to maintaining frequency stability becomes more complicated in each of the islands, as the cumulated inertia constants are evidently smaller in the islands and the frequency response to power balance consequently larger.

Thus, the importance of providing the network with additional inertia and dispatchability is eminent, and these measures therefore may be regarded as adequate for quantifying a wind turbine or a wind farm’s contribution to maintaining frequency stability.

D.2.3.2. Power oscillations and small-signal stability

As discussed throughout section 3.3.2, regarding electric power systems as electromechanical systems provides some understanding as to how the static picture of such a system is. What is actually the case is that the electric power system virtually puts all generators on “the same” rotor shaft, through the electric power system – how closely they are connected of course depends on the network conditions.

Still considering the system as an electromechanical system, all these generators, with their respective mechanical power sources, that are virtually connected together by the network interact with each other as all interconnected systems do. As the power production is not constant over time, changes happen in the respective production of each of the producing generators. These changes in production can reveal them selves in oscillations in power production, resulting in oscillations in generator rotor frequency and power flows in the electric power system, to which they are connected, henceforth known as power oscillations (discussed in Appendix C).

Many kinds of disturbances may cause electromechanical power oscillations, such as generator trips, switching or other phenomena that “hit the right frequencies” (i.e. the eigen-frequencies of the system). One eminent source, which could be regarded as one of the most latently dangerous ones, is fluctuations in the power production. Considering power production from an electric power source over time, if certain frequencies occur in this “power signal”, that are close to eigen-frequencies of the electro mechanical system that an electric power system represents (or harmonics hereof), there is a risk that it may result in a more or less damped (or eventually un-damped) power oscillation, where production of power swing from one generator to another back and forth. This may result in overloaded lines, and overloaded generators, that eventually may trip, causing serous damage to equipment and operation, including blackout.

One way of evaluating whether or not a wind turbine or a wind farm may cause electromechanical power oscillations is to consider the spectrum of power that it produces when connected to an ideal generator on an infinite bus. The content of oscillating power can then be evaluated, and from this it can be shown whether or not the wind turbine or wind farm may cause power oscillations. In general the lower the content, the better the wind turbine.

D.2.3.3. Dispatchability

A feature about any kind of electric power production facility, that is of high importance is how well one can control the power output from the facility (as a whole) – the better one can control and pre-determine the output of active and reactive power and the faster it can be regulated, the higher a dispatchability can the power production facility provide, and the better a power quality with respect to dispatchability. Improved dispatchability yields easier operation.

This also applies for wind turbine systems, though previously they have not proven to be the most dispatchable electric power generators available, mainly due to the lack of control of the mechanical power source, and due to the lack of control of the reactive power output as well (as asynchronous generators was used). But as active power regulation, e.g. as pitch regulations has been improved and more widely used, wind turbines have improved with respect control of the active power output, and with reactive compensation devices and new generator technologies, such as double-fed asynchronous generator, also the lack of reactive power output control has been dealt with.

Quantifying dispatchability is, however, a matter that has not been dealt with, as a measure, which is adequate for the phenomena, is not directly at hand, but relies mainly on a survey of more or less objective character. Therefore, an assessment of how the dispatchability is of a distinct electric power source, say a wind turbine or a wind farm (or what ever relevant), must anyhow rely on a description of the control and dispatch possibilities of each distinct facility, maybe accompanies with relevant data, such as the maximum ramping of the power and the maximum possible power production (i.e. the rated apparent power)[23]. One approach towards describing the dispatchability of a certain electric power source is to compare the described electric power source to a conventional power plant of the same rated size, driven by a steam turbine as mechanical power source, as this is considered as the ideal reference, but many other ways of doing it may prove favorable.

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[23] It should be stresses that even though these quantities say something about the wind turbine power quality with respect to the dispatchability, they do not represent an adequate measure, as dispatchability includes more than these phenomena.

D.2.4. Quality of wind turbines related to reliability

D.2.4.1. Availability and reliability under steady-state conditions

D.2.4.1.1. On availability and reliability

In the assessment of the quality related to the power production, the availability and reliability of the wind turbine also has importance, as it has in general regarding electric power sources. When evaluating the availability and reliability of a distinct electric power source's supply of power, various measures may seem adequate for quantifying the quality provided.

Availability and reliability are in nature two aspects of the same problem, but they seen as measures of different features. Where availability measures the degree to which the electric power source is "at hand" providing a service that can be exploited at will, reliability concentrates more on when the electric power source is not out of order due to some reason. Subjectively, availability has a more positive sound than reliability, as reliability is a measure of when you cannot count on a power source, whereas availability regards when it is available. In this discussion they will be regarded as the same, and the terms will be used synonymously.

D.2.4.1.2. Quantifying availability and reliability

The simplest quantification is to estimate the total production capability over a period, say a year, measured as the amount of energy produced. Hence, the availability of a wind turbine will be expresses as the amount of MWh's produced over a year.

This measure is only adequate to a limited extent, as this does not provide any information about the how long certain levels of power supply are available, and how often. This information may be essential in relation to estimating the power quality supply in most systems that are constrained by the power production.

Thus, it is necessary to provide a measure, that gives information about for how long the wind turbine is available for supplying a certain level of power throughout a year. This can be expressed as e.g. a percentage of time where the wind turbine is capable of providing its rated power, or as the expected hours during a year the wind turbine can be expected to provide a minimum of e.g. 85% of its rated power. Various measures can be constructed, and the method can be extended by estimating the distribution of available power production capability over the year, e.g. by estimating how many hours during a year the wind turbine is capable of providing 100%, how many hours it is capable of providing more than 85%, how many hours more than 70%, etc. Such a power production capability assessment provides far more information than the above given measure, making it a more adequate measure, when more production levels are available.

What this measure lacks is the relation to the load has to supply. A way of taking this into account is to use the measure loss of load probability (LOLP) index for the wind turbine.

The LOLP-index evaluates the latent risk of falling short in power production capacity with respect to the actual load over a distinct period of time, e.g. a year. The index provides a measure for the adequacy of the specific installation in relation to the load that it should supply. This measurement really is designed for is for evaluating the total production in an electric power system as a whole, considering the total available production and comparing it with the load distribution of the system. The problem about this measure is then to define how the load to which the availability is referred. One approach could be to generate a normalized load, that is the actual load distribution of the regarded electric power system where all the respective values of the load has been normalized to the rated power of the wind turbine. From this, the production availability can be related to the load structure, providing a picture of the wind turbine’s capability to supply a normalized load. Such a normalized loss of load probability (NLOLP) may provide a fairly adequate measure for how well the wind turbine match the consumption in the distinct electric power networks. An graphical example of how to evaluate the NLOLP of e.g. a wind turbine is shown in Fig. 28.

A draw back of this approach is that it does not deal with the probability that a production period, where the available production is e.g. high, falls together with the time period where the load is high. Making an assessment that takes this into account would further enhance the assessment. However, such assessments would probably have a number of assumptions, which makes it virtually impossible to attain a reasonable measure.

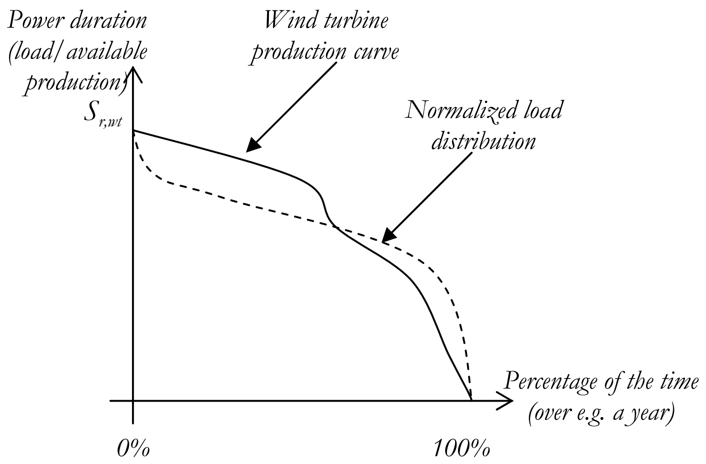

Fig. 28. Illustration of possible assessment of wind turbine availability using NLOLP; the estimated production availability of a wind turbine is assessed at different levels of power, and compared to a normalized load curve. From this, the adequacy of the available power production of the wind turbine compared to the distinct load can be assessed. In the fictitious example shown above, the wind turbine fully meets the demands of the consumption of the load approx. 60% of the time (i.e. when the wind turbine production curve is above the normalized load curve), but comes short in the remaining period.

D.2.4.2. Short circuit support, contribution to short circuit power and ancillary services such as black start capability.

When it comes to faulty operations, the power quality supplied may become more important than at other times. Often, being able to supply the consumers with electric power even when faults occur provides the consumers with the most fundamental power quality feature, being able to sustain supply (as discussed in section 2.2.). For wind turbines, power quality assessment with respect to faulty operation is of importance too.

Some of the features that are important to evaluate as power quality drivers with respect to faulty operation are whether or not the wind turbine or wind farm is able to support the electric power system with continuous power production even under faulty operations, how much it contributes to the overall short circuit power level of the system, and whether or not the wind turbine or wind farm provides black start capability, i.e. can be used as a start-up if restoration from a total black out situation should be needed.

Whether or not a wind turbine or a wind farm is capable of sustaining power supply even during faults is important with respect to power quality, as the harsher the conditions the wind turbine or wind farm can sustain production under, the longer can the supply to consumers be sustained, and the better the power quality provided to them. Measures of how capable a wind turbine is of sustaining supply can be e.g. the level of short circuit power it can provide over a certain period of time, or the contribution to the short circuit power it provides.

The contribution to the short circuit power is, apart from a measure of the wind turbine quality to support during faulty operations also a measure, that indicates further improvement of the power quality with respect to e.g. harmonics, voltage and frequency stability and other features. Therefore the short circuit power contribution is an important measure for evaluating the power quality of a wind turbine in general.

Also of importance is whether or not the wind turbine or wind farm is capable of supplying different kinds of ancillary services such as black start capability. In general, the more different kinds of ancillary services that are provided, and the better the quality of these ancillary services are, the more does this contribute to the assessment of the power quality provided.

D.3. Concluding remarks

The importance of power quality in future is evidently high, as it may be the prime value driver in the electric power market. Therefore in the future, liberalized power markets the assessment of the provided and consumed power quality from production and consumers of electric power becomes more and more vital.

Power quality, however, consist of many distinctive features of more or less objective and technical character, and new aspects of what power quality consist of may be added as time goes by. Some features can be quantified (to a certain extend), some cannot and remain qualitative.

As power quality is of such a complex and dynamic nature, the assessment of it is complicated. Thus, desiring to assess this phenomena in relation to the provided power quality of a wind turbine or a wind farm (in e.g. a tariff situation) is of importance, but must rely on providing an overview, a "power quality scorecard" of the wind turbine or wind farm.

The content of such a power quality scorecard can be the e.g. the measures given above – adapting it to what is relevant in each situation, by either removing or (most likely) adding measures of power quality features, which may have relevance.

APPENDIX E : LIBERALIZATION ASPECTS OF POWER QUALITY AND POWER SYSTEM OPERATION

E.1. New rules for the chess-game

E.1.1. From governmental monopoly to liberalized market

In the EC, electricity markets are being liberalized, on the demand of the European Commission. Many places, the liberalization process has already taken place, or at least been started. A regularly used approach is to liberalize the production/generation (generators) and vendor/retail segments (power companies), and to keep transmission and distribution as natural, governmentally controlled monopolies (network companies). Whatever the approach has been, the problem still remains: how to make the liberalized power market a success – how to drive value for both all along the value chain, for generators, power companies and customers.

Many places where the power market has been liberalized, the mobility of the customers is relatively low, as the customer benefit, that can be achieved is relatively small. Hence, the electric power market is functioning inefficiently, which is not good for either the customers or society. Neither is it good for the companies, as the low mobility makes it harder to develop and grow.

The easy one to blame is the commodity itself: To many customers electric power a uniform commodity – they don’t care who’s delivering it, as long as it is cheap.

Generators and power companies ought to blame them selves for giving the customers this belief – because electric power is not at all a uniform commodity. The quality of electric power can vary a lot. However, from the monopoly period, most customers haven’t ever been confronted with this fact, which may be a vital value driver for the electric power business.

Liberalized power markets are to rise on basis of the former regulated markets, where the common kind of regulation was cost-based. Electric power companies were awarded/assigned to a certain geographic site, in which they were to supply electricity as good as they could, as cheap as they could. Planning and building of plants and electric power systems was carried out centrally and often under high political interest, and operators on the electric power market were to bill the consumers only what was needed to cover the cost, and in the most liberal cases a just and reasonable rate of return on the invested capital. More or less, it has acted as a part of the public sector, whether the formalities made it or not – a public commodity provider with high public need and support and an increasing ability to serve the public effectively. In the early days, when service was less effective, the political focus on improving the electric power utilities where higher, but as services was stabilized, the political focus became smaller and smaller[54]. See Fig. 29.

This caused a dilemma, where electric power became almost anonymous, without any focus at all, as long as services were effective and stable, and only got focus, when services were interrupted – and then of the more negative kind. Thus, only limited demands to operations (but technical demands) were ever placed from political hand on the electric power utility.

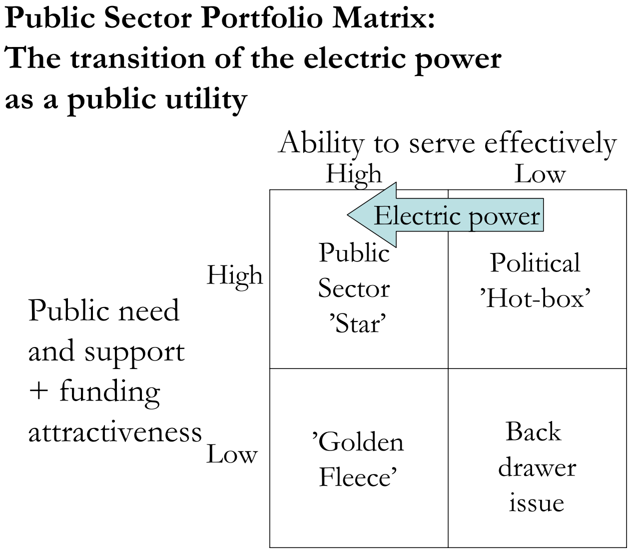

Fig. 29. Regarding electric power as a public utility; As service became more and more stable, the political focus on improving the service became smaller and smaller. This is a dilemma for the electric power utility: When thing go right, you have no focus at all – when things go wrong, you have all the negative focus[55].

Then an end came to regulation, in the name of liberalization, and utilities became businesses and consumers became customers. The problem though persists, that many in the business still act as utilities and many customers act as consumers.

E.1.2. Latent risks – if nothing is done

The electric power business is in many ways different from other businesses. E.g. when NASDAQ was almost halved in the spring 2001, the prices for stocks in the US electric power companies rose, even significantly[56]. However, the fundamental principles of making sustainable business still apply – principles like a demand for a generic business strategy[54][68-72].

In the US, regulation was given up in the late 70'ies and early 80'ies. As expected, deregulation has given rise to a new breed of highly profitable electric power production companies and electricity traders, but due to lack of strategic focus, the electric power business faces a potentially shake out as supply catches up with demand. In the Scandinavian region, this is an emerging problem as well, causing a tight electric power market with spikes high prices[58][58]. The reason for these tight production margins is that it is simply not attractive enough to make investments in the needed production facilities, because there is no value driven in the business.

This is a problem in the business in general, that has to be coped with, as it threatens its future. Therefore a fundamental change in strategic thinking is needed in a liberalized market.

E.2. Need for re-thinking the business strategies

E.2.1. Generic strategies and strategic choices.

Naturally, understanding how liberalized markets work can better equip their participants to operate in them. Implications are different for generators, for retailers and for customers, as well as for regulators, but they all have to achieve the same: perceive added value from being in the market.

Generally, a business should take into account the opportunities and threats the environment presents, and support the core-competences and the resources that the company has. This of course also apply to companies in the electric power business. There are three generic strategies for driving value in a competitive market[60]

- Cost leadership
- Differentiation
- Focus or adaptation

Cost leadership is about winning in the competitive market by having the lowest costs, and hereby achieve higher margins than the competitors. The problem is that there can be only one number one, making it hard to be number two, thus making the competition in an environment of cost leading fierce and destructive.

Differentiation is about adding value by being different, either by adding value to customers by supplying commodities that they demand, or by adding demand for commodities to customers that can supply value. Apart from competition in a cost leadership environment, each different actor in a competitive environment of differentiation can become a success. That makes the competition is often less fierce, as companies compete in different fields.

Focus as a strategic basis has both a cost leadership and a differentiation aspect. Some customers demand low-prices, some demand specific commodities, that specifically suit their demand. When adapting a focus strategy, a company should be able to provide the niche, that it is focusing on with commodities that gives perceived added value for the customer.

In the regulated times, the focus was on keeping the technical conformance of the electric power high and the cost of electricity low – so to speak, a kind of cost leadership-strategy, but without any competition. It is not hard becoming the best in the field, when you race alone. Back then, it was possible to maintain planning and investment on a sufficiently high level to have a sustainable development in the electric utility. The question is whether adapting a cost-leadership strategy is a viable and sustainable strategy in a competitive, liberalized market. Choosing a cost leadership strategy is only sustainable if the company is number one – else, it’s a strategy destined for ultimate failure.

In a competitive, liberalized market there are several strategic options of how to develop the business. See Fig. 30.

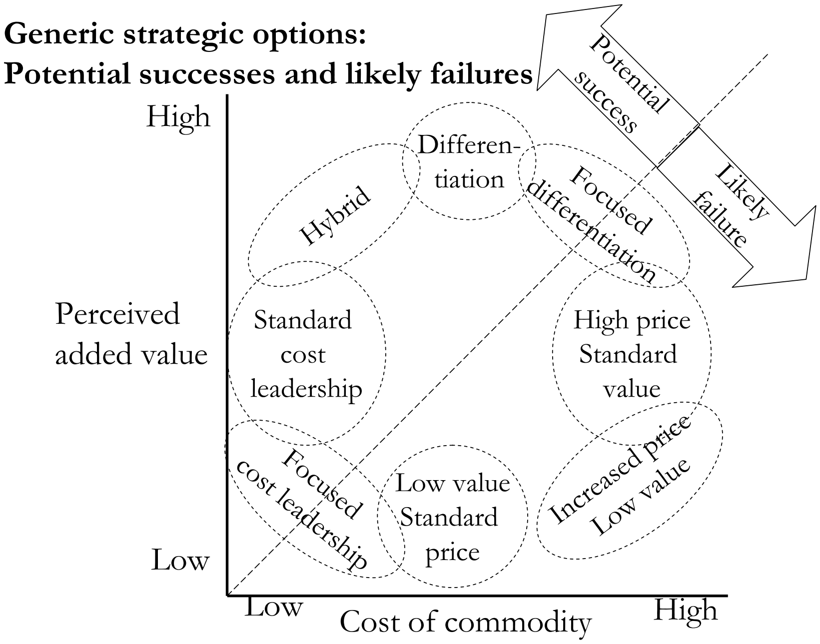

Fig. 30. Generic strategic options in a competitive market[64]

Attention must be directed towards adding perceived value to the customers, and hereby also itself.

As for the time being, companies in the electric power business have locked themselves on a fixed perceived added value. From back in the regulation times power is considered a standard, uniform commodity. To most, power is just considered power, regardless the quality of the electric power delivered - however, it is a fact that there are many quality features, both technical and non-technical, that makes the quality of electric power vary. But customers are not confronted with them, thus no demand for them is generated, and no added value is perceived by getting higher power quality. Seemingly, price is the only competition parameter, driving the companies to a fierce competition on lowering costs, which in both the short and the long run limits the interest in investing in new production facilities, and leads to a self-destructive development. However, in the longer run, the prices have to rise in order to make the necessary investments to keep the electric power system running, but without adding new perceived value – an unsustainable development, that may risk lack of possibilities to invest in the needed production facilities and hereby risk a California-style power crisis.

E.2.2. TOTAL POWER QUALITY AS A VALUE DRIVER

E.2.2.1. Defining power quality

How to define power quality is a matter that is discussed widely, as there exist no formal definition of power quality that is accepted everywhere. A usable definition of power quality may be as follows:

Definition - Power quality is all the features of the electric power supply, in addition to the amount of energy supplied, that add value for the consumer.

This definition is quite wide in its nature, and includes both the technical and the non-technical quality features of the electric power, as illustrated in Fig. 31.

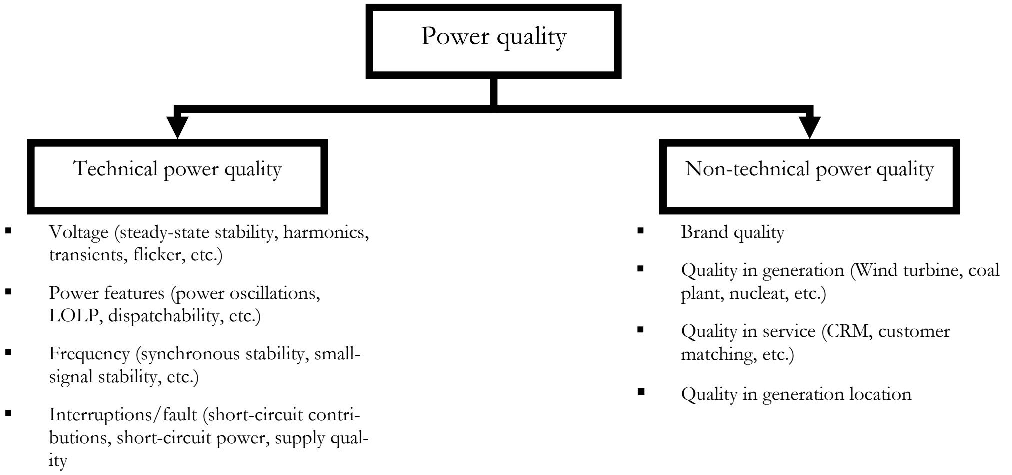

Fig. 31. An overview of power quality; classification of power quality features. Noteworthy is that the technical power quality features are usually quantitative and objective features, and non-technical features are usually qualitative and subjective features.

Traditionally, only the technical features of power quality have been considered, as also discussed in Appendix D – a point of view that only observes the conformance quality of electric power[73-74]. However, it is evident that there is more to power quality than technical power quality, and this simple-minded picture of what drives the value for the consumers is incomplete. This definition regards power quality in a total quality sense, referring to what is regarded in total quality management (TQM), and not just a conformance quality[67].

In a future liberalized electricity market, working under market conditions, it is important to know what drives the value for the consumers, as the critical success factors for any electric power supplier will be to supply power with the proper quality.

There will be an on-going demand for total power quality in the future, as discussed in Appendix D.

E.2.3. Power quality as a value driver

The nature of power quality, as discussed in Appendix D, where it adds value both to the customer and to the companies in the electric power business ,and the fact that it is increasing in demand in the long run, makes it rather suitable as a central value driver in the central strategic considerations for a company in the electric power business.

Furthermore, the fact that the demand for quality differs from consumer to consumer, makes it viable for companies with more differentially oriented strategies to operate.

The problem is that the demand for power quality is not recognized – but as e.g. was the case for mobile phones for just 8-10 years ago, demands can be created by proper marketing.

E.2.4. BREAKING THE CIRCLE OF COST LEADERSHIP COMPETITION

If the risky development caused by singleminded betting on cost leadership strategies should be broken, the need for a strategic change in the companies of the electric power business is eminent. Depending on where in the value chain a company is placed, the approach may be different

E.2.4.1. Strategies for electric power producers

Electric power producers actually have a variety of market segments to service; some that have stable prices, but lower risks, others that have higher risks, but potentially higher rewards. As an example of a high risk market with high rewards, the regulation power market can be mentioned.

Electric power producers have to strategically choose which markets to »play« in. The choice should reflect the financial position of the company, the current profile, risk-aversion level, and the culture among stakeholders. Driving value by operating in some of the more risky market segments would demand new technical skills. But choosing different strategic options than the competitors makes it possible to break the limits of cost reduction, and instead focus on driving new value.

The opening of new market segments with higher value driving than the conventional “one-standard” electric power market will most likely ensure better conditions for the crucial timing the investments and assets restructuring, and ensure that new production capacity is brought on line just as the market reaches utilization levels beyond safe operation – e.g. approximately 80-85%[59].

In a more differentiated and focused electric power production market, prices are likely to be higher and steadier, but so is the perceived added value too.

E.2.4.2. Strategies for electric power retailers and customers

Focusing on the demand for provided power quality may be a way to ensure the value adding along the value chain in the electric power business for both retailers and consumers. Though, the obligation to ensure that the focus is on provided quality is on the retailing side, on order to drive the demand for a specific level of power quality on the customer side. Since prices in a more differentiated and more focused market, the only way to ensure sustainable development in business, the perceived added value must be passed on.

Strategic development along different directions, by e.g. introducing new products and/or new markets is another way of adding value to customers, that are not focused on power quality at all. Such diversification strategies demand development of either products and/or markets, to ensure its success, and attention should be on whether the core competences are still sufficiently protected. If e.g. a power retailer introduces broad-band internet as a diverse product to its customers, attention should be on whether this diversification actually adds value to retailing of the core-commodity which is selling power.

APPENDIX F : ON ELECTRIC GENERATION SYSTEMS

F.1. Introduction

Generation of electric power in larger scale, i.e. for consumption in electric power systems, can be done using different technologies, and using different principles. Most common is the principle of converting mechanical power into electric power applied, using the Faraday law of electro-motional induction. In most appliances, this is done in electric machinery, designed for production of alternating current (a.c.) electric power in a rotational electric machine.

Generating electric power by using a rotating electric machine involves the conversion of mechanical power to electric power by revolving a rotor with some kind of magnetic field inside of a stator, on which is mounted stator (armature) windings. The transformation from mechanical energy to electric energy takes place in the air-gap between the revolving rotor and stator, in which magnetic fields, generated from currents in the armature windings, create a “breaking-torque” on the revolving rotor – consequently, the revolving rotor has to be supplied with some kind of mechanical power to maintain a balance.

Thus, if a rotor field is available, and if mechanical power can be supplied as a torque on the rotor, electric power can be generated. Usually, the mechanical power is supplied by e.g. a steam turbine, a gas turbine, a diesel engine or wind turbine blade rotor, and is as such not creating the most crucial constraints on the generator. How the generator supplies the rotor with a magnetic field is where most generators differ.

In this appendix, the two fundamental types of electric generators are discussed briefly: the synchronous machine and the asynchronous machine.

F.2. synchronous generators

The basic principle in a synchronous generator is that it excites its rotor with a magnetic field, which is generated by an external exciter (i.e. an external electric voltage source). The rotor then revolves at a speed that corresponds to the system frequency, generating a.c. voltage and current of the same frequency, as the fields of the rotor and the stator interacts. The interaction of these two fields then results in a transfer of mechanical power from the rotor to electric power in the stator.

An important fact is that when using a synchronous machine as a generator, both active and reactive power, as well as voltage level can be controlled – on the other hand, apart from providing the possibility of control, it can be argued that synchronous machines actually demand this kind of control; thus synchronous machines are not necessarily desirable at locations, where these control possibilities are not wished for some reason (e.g. due to the higher degree of maintenance that follows). Synchronous generators are therefore, when it comes to a stability and control point of view, wanted in places where a control possibility is needed.

If subjected to some kind of load, the power generated in the synchronous machine will be transferred to the load electrically, and dispersed there. The application of a load will result in a voltage drop, due to the load current; however, this voltage drop can be compensated by increasing the magnetization of the rotor, i.e. by changing the rotor excitement. This can be controlled by e.g. some kind of automatic voltage regulation mechanism. This externally provided excitation of the rotor, and the consequent possibilities of voltage regulation makes it possible for a synchronous machine to attain and sustain a voltage level in an electric power system, even if there is no other means of attaining it, depending (of course) to which level, the electric power system is loaded. A synchronous machine can be used to start-up electric power systems, in which no voltage level is excited, and can be used for maintaining voltage when started up – a synchronous machine can operate under isolated conditions.

Further more, synchronous machines can be used for attaining the electric power system frequency, as the machine operates synchronously.

Even when taking into account the losses from the excitation of the rotor, the synchronous machine is in most cases the most energy efficient kind of generation. This is part of keeping the direct operation costs limited, looking apart from maintenance. This, together with the possibility of being able to control power flows and voltage level, together with the possibility of being able to operate under islanded conditions, may lead to the conclusion that the synchronous machine is better suited for some kinds of application. However, the construction and investment costs together with the maintenance costs of synchronous machines may change this picture, as they both are higher than for other kinds of generators. Most commonly, synchronous machines are only applied where there is a need for the possibility of operating under islanding conditions or when the need for control can justify the extra expenses.

F.3. The asynchronous machine as a generator

The asynchronous machine consists of a rotor that revolves inside a stator. In the rotor, a field is induced by the a.c.-currents in the electric power system, resulting in an alternating rotor field, which itself changes direction together with the a.c.-currents in the electric power system. The fields in the stator and the rotor result in a rotational field, which will cause the rotor to revolve at the same angular velocity as the field, if unloaded. If subjected to a load, the rotor will be »braked« mechanically, resulting in the rotor and stator fields to come out of synchronism, by rotating lower than the stator field. When out of synchronism, the stator field will try to regain synchronism by applying an electro-mechanical torque on the rotor, which causes an increased current in the stator, flowing from the electric power system and extracting electric power from it.

When the rotor is supplied with mechanical power (i.e. when the asynchronous machine acts as a generator) the opposite mechanism is the case; the mechanical power applied on the rotor results in a mechanical torque, which then causes the rotor, and the rotor field, to revolve faster than the stator field. In order to regain synchronism, the stator reacts by trying to brake the rotor, by applying an electro-mechanical torque on the rotor, resulting in a current flowing out of the stator to the electric power system, supplying electric power to the system.

Worth noticing is that the asynchronous machine rotor is not externally excited, but excited from the electric power system, an in a manner, which does not provide the possibility of controlling it – on the other hand, it does not demand any regulation; the rotor exciting is self regulating, but relies on the presence of an electric power system voltage. Furthermore, there will be a consumption of reactive power in the stator and rotor circuits when operating, both as a motor and as a generator, as the current that flows for applying an acceleration or braking torque has to flow through the machine windings, which are highly reactive. Thus, the asynchronous machine cannot be used for supplying reactive power, as it will, dependent on the load or production, consume it. The only way of controlling the reactive power consumption is by limiting the load or production – i.e. active load/production and reactive power consumption »goes hand in hand«, and can therefore not be controlled independently.

When it comes to the losses, the asynchronous machine usually has a higher level of losses, compared to the synchronous machine. On the other hand, the manufacturing costs and the maintenance costs are much lower especially when it comes to smaller machines, which is why it is very commonly used as e.g. generator in small-scale production facilities such as wind turbines. However, the lack of control over the reactive power production and voltage level, as well as the fact that asynchronous machines cannot operate alone under islanding conditions (where no magnetization of the machine rotor from the electric power system is available) is an eminent back draft of the asynchronous machine appliance as generator, especially when more and more of these independently small production facilities such as wind turbines are put in service. Then, the lack of control may become to a serious problem.

F.4. The doubly fed generator

The doubly fed asynchronous machine is by many considered as a kind of »hybrid« between an asynchronous and a synchronous machine, which to some kind of extent is true when it comes to the operation.

Principally, doubly-fed induction machines operate as an asynchronous machine, i.e. with an alternating field in the rotor, apart from the standard asynchronous machine the rotor field is not induced directly from adjacent electric power system (to which the machine is connected), but is induced by an external excitation supply. Usually, this external excitation supply consist of a a.c./d.c.-d.c./a.c.-converter system, based on power electronics, which is connected to the adjacent network near the terminals of the machine. The machine can then be operated as either a motor or as a generator as an asynchronous machine, depending on the electric slip that the rotor operates at.

The converter mainly serves one purpose, which is to supply the rotor circuit with excitation, which is fully controllable. The supplied excitation current is in general an alternating current, as for the case of the asynchronous machine, but the controllable converter system makes it possible to control the frequency of the alternating current supplied to the rotor, which again makes it possible to fully control the electric slip, and make it dynamically independent of the mechanical rotation of the rotor. For example, if a double fed generator is applied as a wind turbine generator, the rotor system can be mechanically accelerated up during a wind gust without the electric slip changes; thus, the extra wind energy, featured by the wind gust, does not manifest it self as an increased electric power output from the wind turbine, but as a temporary acceleration of the mechanical rotor system, which then, on a larger time scale can be leveled out. The converter system makes the control of the faster variations in the production of wind turbines easier, using only electrical means of control, and may therefore decrease the negative effects of fluctuations in active power production of wind turbines. However, the long-term and larger variations in the supplied power cannot be leveled out from this technology alone.

As a corollary, the converter system makes it possible to perform dynamic reactive compensation at the terminals of the machine, as the converter system connected to the network may be used as a power electronic static VAr-compensator. Thus, a full double fed generator system may feature a higher level of control over the reactive power flow as well.

Doubly-fed generators as such initially rely on the presence of a certain level short-circuit power in the network to commence operation, in order to supply the rotor with excitation – however, when operating, double fed generators may support the network, and may operate under islanding conditions. Thus, the double fed generator may be used for operating under islanded conditions, to support the network, but may not be used for black start, unless if the converter system is equipped with some kind of electric power source (e.g. a battery-bank) for supplying initial rotor excitement.

The technology behind the double fed generator is not new, but the application of the double fed machine as a generator in e.g. .wind turbines is – probably as it is only recently that the demanded power electronic technology for providing the needed control of the rotor excitement has been developed at a reasonable level and at a reasonable price. The losses of the double fed generator are to a certain extend comparable with the ones of the asynchronous generator, but the double fed generator demands more maintenance (due to the more complicated rotor excitement and excitement circuits) and has higher investment costs. This cost structure may be the reason why the double fed generator is not commonly used yet, even though it has some operational advantages when it comes to the electric behavior related to stability and control.

APPENDIX G : SHORT ON VARIABLE WIND TURBINE SYSTEMS

G.1. Variable speed wind turbine principles

G.1.1. Converter based concepts

One way is to separate the wind turbine power conversion system (i.e. the wind turbine blade rotor, gear box and generator) and the electric power system, i.e. not to connect the wind turbine generator directly to the electric power system. Separating the two systems makes it possible to operate with different system frequencies in the wind turbine system and the electric power system; hence, the system frequency can be adapted over time in a manner that limits some of the faster dynamics of the wind turbine and/or in a manner that enables an optimal conversion from wind to electric power. If designed properly, the wind turbine conversion system can even be optimised for operation at a mechanical rotational speed, which makes the gearbox obsolete – this demands that the blade rotor rotates at a relatively slow speed and/or that the number of poles on the generator should be increased to match the blade rotor speed.

The separation can be made using a simple frequency converter system, which is basically a a.c./d.c.-c.d./a.c.-converter system. The principle is shown in Fig. 32.

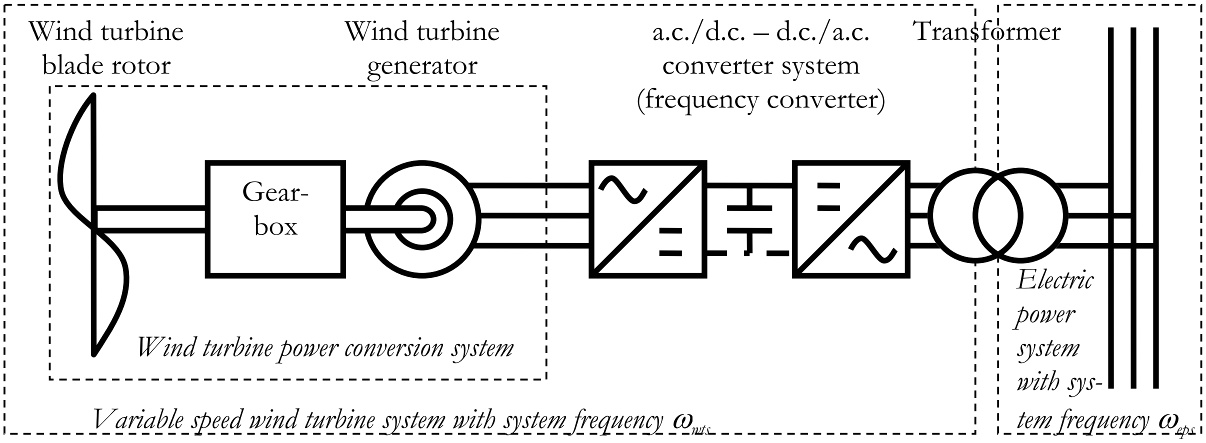

Fig. 32. Variable speed wind turbine system concept, using separation between wind turbine power conversion system and the electric power system; the wind turbine blade rotor provides mechanical power (as a mechanical torque) through a mechanical gear box system to a wind turbine generator rotor shaft, and the wind turbine generator converts the mechanical power to electric power. The wind turbine power conversion system (blade rotor, gear box and generator) is separated from the electric power system by an a.c./d.c.-d.c./a.c.-converter system (frequency converter) which enables the wind turbine power conversion system and the electric power system to operate at different system frequencies (ω_{wts} in the wind turbine power conversion system and ω_{eps} in the electric power system). The frequency converter should be capable of supplying some reactive compensation, and should enable full control of the wind turbine power conversion system frequency. Such systems are commercially available; they can eventually, in the future, be extended to feature some kind of d.c. electric power storage (e.g. batteries, large capacitor banks, future hydrogen storages or future SMES-storage systems) for short-term or long term storage in the future.

When using a frequency converter as separator the electric power is generated from the wind power in the wind power conversion system as an a.c. electric power at the wind turbine system frequency, ω_{wts}, which is then converted to d.c. electric power which then again is converted to a.c. electric power at the electric power system frequency, ω_{eps}, and supplied to the electric power system. Thus, all of the produced power must pass through a converter system, which often results in larger operational losses. Also, the investment costs of variable speed wind turbine systems are in general larger than the corresponding fixed speed wind turbine systems, mainly due to the introduction of the converter and its control equipment.

The wind turbine power conversion system can either be based on an asynchronous generator or a synchronous generator.

Using a standard asynchronous generator in a frequency converter separated variable speed wind turbine system features some latent problems, as many conventional frequency converter systems are not capable of supplying the necessary reactive power for exciting the rotor in the generator. However, if the frequency converter system is capable of providing the needed reactive compensation and if the frequency converter is capable of maintaining an operationally acceptable short-circuit level inside in the wind turbine power conversion system, most of the benefits of from the fixed speed appliances of standard asynchronous generators must be expected to reappear in this variable speed design (e.g. damping of dynamics, and low investments and maintenance costs). Using IGBT-based converter systems may provide the frequency converter with these features – though, often IGBT-based converter systems have relatively larger operation losses and are more expensive when it comes investments. If set in service, such systems will have a possibility to vary the speed of the wind turbine to a much larger extent than the fixed speed wind turbine systems with asynchronous generators, which will provide an even better damping of the dynamics of the produced electric power and will introduce a possibility to adapt the blade rotor speed for optimal performance at the actual wind speed, for better utilization of the available wind power.

Basing the wind turbine power conversion system on a synchronous generator for power conversion in such a converter separated variable speed wind turbine system reduces (if not eliminates) the need for converter capability of supplying reactive compensation, making it possible to use a simpler converter technology. Further more, the introduction of the converter reduces the risk of the synchronous generator loosing synchronism, as the converter can increase/decrease the wind turbine power conversion system frequency at will, making it possible to accelerate/decelerate the wind turbine blade rotor to control the torque of the generator rotor, making it possible to absorb dynamics. In fact, introducing a frequency converter in synchronous generator based wind turbine system eliminates many of the problem; s related to dynamics present in the corresponding fixed speed wind turbine system; however, the investment and maintenance costs of synchronous machines are still higher than for the equivalent asynchronous generator based systems, and the introduction of the converter does not lower neither the investment or maintenance costs, nor does it lower the operation losses. Further more, if the used converter technology is not itself capable of supplying reactive compensation for the electric power system or the wind turbine power conversion system, the reactive power consumption of the converter system may be considerate, and may affect the voltage stability, dependent on the properties of the electric power system.

G.2. Directly coupled variable speed wind turbine concepts

Another way of obtaining independence between the system frequencies of the wind turbine conversion system and the electric power system is by making the generator rotor capable of rotating at different mechanical frequencies without it changing its electric frequency; that is, maintaining the apparent revolving of the rotor field at the system frequency of the electric power system, but making it possible for the rotor to have a varying mechanical rotational speed. This requires that an a.c. field is present in the rotor, for which an adapted asynchronous generator is suited. The two most common methods for obtaining this is using an asynchronous generatore with either slip-control or rotor cascade systems or using a double fed asynchronous generator

Slip-control in an asynchronous generator is principally based on the introduction of some controllable resistances in the rotor circuit, in which power can be dissipated under controlled circumstances. This can be used for controlling the resulting power conversion of a wind turbine power conversion system to damp dynamics in the power production, as the output can be smoothened by dissipating the dynamic power fluctuations in the rotor circuit. By making this dissipation, an increase of the slip, and hereby a (somewhat slight) increase in the speed of the wind turbine blade rotor, can be made without a resulting increase in the output of electric power to the electric power system, as the left over power is then dissipated as heat in the rotor circuit resistances. The dissipated power is then lost, but does not invoke dynamic changes in the power output of the machine. This kind of regulation is mainly for levelling out the dynamics of the power production out more than adapting the wind turbine blade rotor speed for optimal performance in its power conversion, as it would lead to large losses in the rotor due to power dissipation, and does therefore not feature as many possibilities for control as the full converter separated variable speed wind turbine systems without loosing efficiency.

Especially when it comes to larger wind turbines, the dissipated power in the rotor circuit may become considerate when using slip control. Thus, instead of just dissipating the left over power in the rotor as heat it can be fed back as electric power through a cascade coupling in an inverter circuit connected to the rotor and the electric power system in parallel with the generator. Usually, these inverter arrangements are made to allow the generator rotor to operate over-synchronously. By feeding back the power instead of just dissipating it, the efficiency of the wind turbine power conversion system is increased, but at increased investments and maintenance costs. And still, the range of varying the wind turbine blade rotor speed is limited, as increased slip will result in a larger transmission through the inverter system, which again results in larger losses in the inverter.

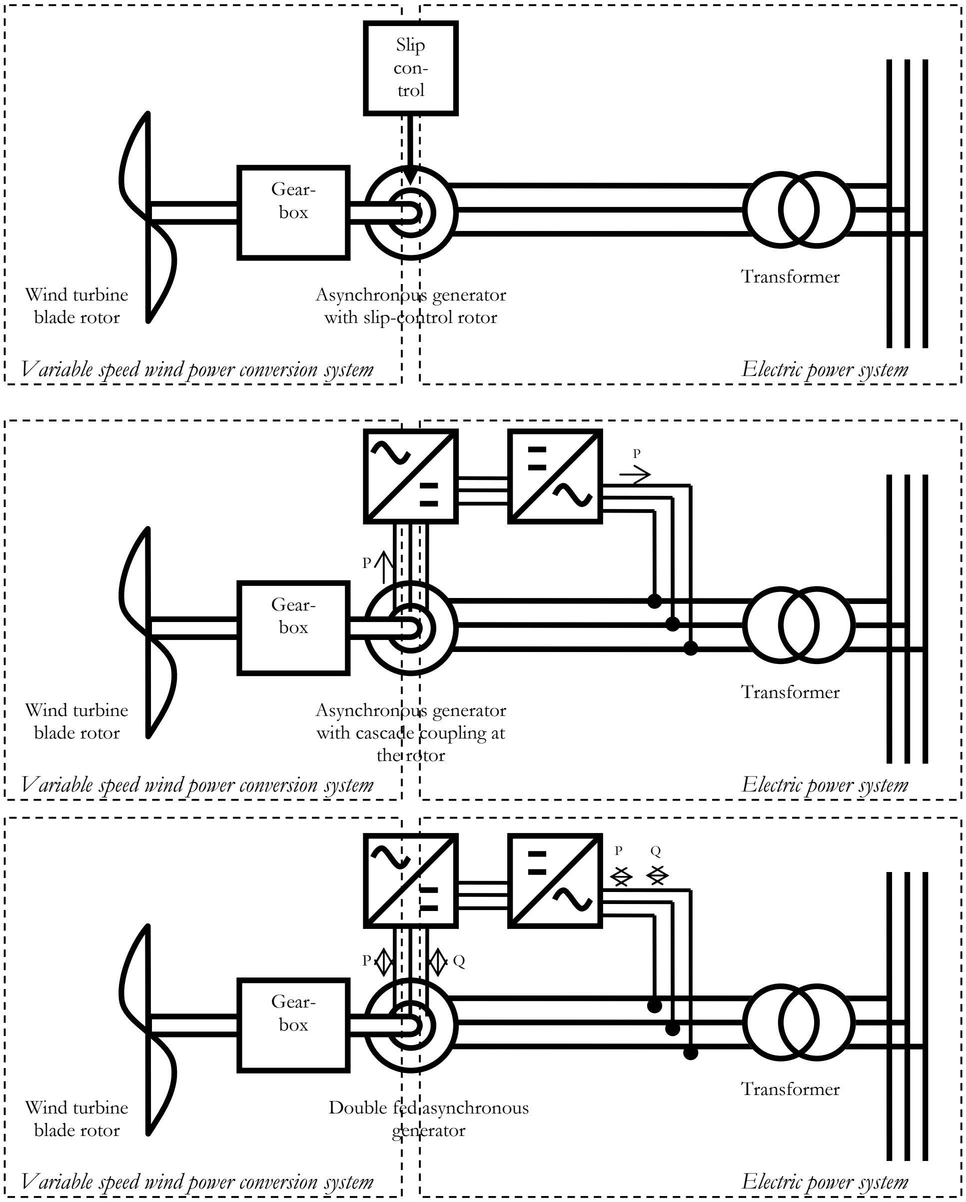

Fig. 33. Different kinds of variable speed wind turbine systems without separation; (top) applying slip-control (using rotor resistances) of the asynchronous generator, (middle) applying cascade-coupled asynchronous rotor with feed back of the rotor power (»one-way« -feed, from rotor to electric power system), (bottom) applying double-fed asynchronous generators with flexible converter system for full rotor active and reactive power control.

Another way of controlling of enabling the wind turbine blade rotor to rotate at a varying speed, is by applying a double fed asynchronous generator as wind turbine generator. The double fed asynchronous generator makes it possible to both feed back slip power from the rotor and to the electric power system and makes it possible to supply the rotor with power from the electric power system, making it possible to operate both over and under-synchronously. Furthermore, double fed asynchronous generator systems normally provide the possibility of making dynamic reactive power compensation, which makes it possible to control the voltage stability impact from wind turbine systems equipped with double fed asynchronous generators, at least to a certain extend. So to speak, it combines many of the operational advantages of synchronous generators and asynchronous generators.

It applies to any wind turbine system that minimizing the investment costs have interest, as the pay-back time for investments are hereby lowered, and the economy of the wind turbine system is improved. The generator of a wind turbine is not an insignificant part of these investment costs, and therefore if the cost of the generator can be reduced, so can the whole economy of the wind turbine. However performance capability and cost of an electric generator are correlated, which means that some of the desired electric and operation features of a generator may be compromised in order to reduce the manufacturing cost. One feature, which is often set aside in order to lower the manufacturing cost is the generator capability to sustain operation during faults in the electric power system, having the effect that wind turbines often trip when the nearby electric power system is exposed to faults. For a single wind turbine, producing only a very small fraction of the total electric power in the electric power system, this effect may seem insignificant, but if the total amount of wind turbines (having this characteristic) is high such tripping/multiple fall-out of wind turbines may have a hazardous impact on operations, and may lead to instability in the electric power system.

APPENDIX H : THE MODEL FOR WIND FARMS

H.1. Model demands and requirements

H.1.1. General considerations

For investigation of wind turbine and wind farm performance, a proper model is needed, which shows correct properties with respect to the investigation objective. In this case, where the overall electric power system stability issues of integration of wind turbines is desired to be assessed through simulations, the model should be developed to respond correctly mainly with respect to the factors that have an impact on stability.

The simulation studies are divided into to overall types of investigation, referred to as small-scale simulation studies and large-scale simulations.

The small-scale simulation studies focus on identifying and exemplifying distinct problems related to the behavior of embedded generation, and regard them isolated. The small-scale studies concentrate on the impact of embedded generation on voltage stability, on small-signal synchronous stability and on the connection method and principle (i.e. voltage level of connection point and whether clustering in wind farms or connecting as distributed, single units are better). Apart from the above given purposes of the small-scale simulation studies they also serve the purpose of validating the models of wind turbines and wind farms.

The large-scale simulation studies investigate the more complex behavior of electric power systems when embedded generation is tried to be integrated in large scale. The simulation studies are split up in studies of two scenarios, that all however regard the (somewhat fictitious) case where the installed production capability of Barsebäck is replaced with embedded generation in the Southern Swedish electric power system, so that the energy production over a year remains the same. The simulations are carried out to investigate the same problems as under the small scale studies, but with a large system point of view, and regarding the problems when these coincide.

H.1.2. Specific model requirements

H.1.2.1. Requirements related to voltage stability investigations

It is of importance to evaluation of voltage stability in relation to wind turbines and wind farm integration, especially when it comes to wind farms consisting of wind turbines based on asynchronous generator technology. Especially the representation of the wind turbine or wind farm with respect to reactive power is of importance, as mainly the reactive power flow, caused by consumption or production of reactive power in the total electric power system, affects the voltage levels in the electric power system.

In the investigations made in this study are made with focus on stability in the time range seconds to minutes, i.e. some sort of dynamic stability without regarding the fast transients. Thus, the representation should be able to reflect the behavior of a wind turbine in this timeframe.

H.1.2.2. Requirements related to frequency and angle stability investigations

When it comes to the frequency stability in relation to wind turbines and wind farm integration, proper modelling is needed especially when it comes to active power, as the balance of active power is the main control parameter for regulation of the frequency. Thus, if the model should be used for frequency and angle stability analysis, it should be proper modeled especially with respect to the active power production, which in its essence is proper modeling of the wind for the wind turbine or wind farm

In the investigations made in this study are made with focus on stability in the time range seconds to minutes, i.e. some sort of dynamic stability without regarding the fast transients. Thus, the representation should be able to reflect the behavior of a wind turbine in this timeframe.

H.1.3. Requirements regarding interfacing with other simulation tools.

The models for the wind turbine or wind farm should, apart from being able to fulfill the above given requirements, it should be able to interface with the ARISTO system, which is a real time simulation tool that can be used for evaluation of electric power systems in stability analyses.

The ARISTO system performs simulations in the positive sequence system, but in real time, and demands model that can be updated dynamically in real time, in order to perform the simulation reliable.

Thus, the model for the wind turbine or wind farm should be able to run in real time, and should be able to provide dynamic simulation data for the positive sequence system of the electric power system in the simulator, based on the actual »situation« in the electric power system which is simulated – thus, it demands a simultanously calculation of wind turbine or wind farm performance under the given electric circumstances. All in all, the model set up for modeling wind turbines or wind farms should be fully able to be implemented in ARISTO.

H.2. Model description

H.2.1. General principles and assumptions

The model developed for this purpose relies on the assumption that a wind farm can be modeled by representing the entire park by a single wind turbine, exposed to an equivalent wind pattern, which is then scaled up to the rated size of the park.. This model should provide a model for the wind turbines solemnly, and is therefore not equipped with any kind of compensation or other compatibility gear (e.g. step-up transformers or switchgear).

The model should be able to, on basis of given voltage and given wind speed, to calculate the response of the wind farm to the adjacent electric power system, with respect to the protection/control properties of the wind farm (based on the common demands for wind farm properties)[24]. Thus, the model is supposed to have interfaces, where interaction between the wind farm model, and wind speed and electric power system properties can occur.

The model is implemented in MATLAB/Simulink, and is supposed to be able to interface with an ARISTO-model, as previously described. Thus, therefore MATLAB/Simulink should be able to evaluate the model respond adequately fast for proper interaction with ARISTO.

H.2.2. The implemented model

H.2.2.1. Overview of the model design

The model implemented in MATLAB/Simulink has an overall layout as shown in Fig. 34. The model consists of 5 subsystems, which interact.

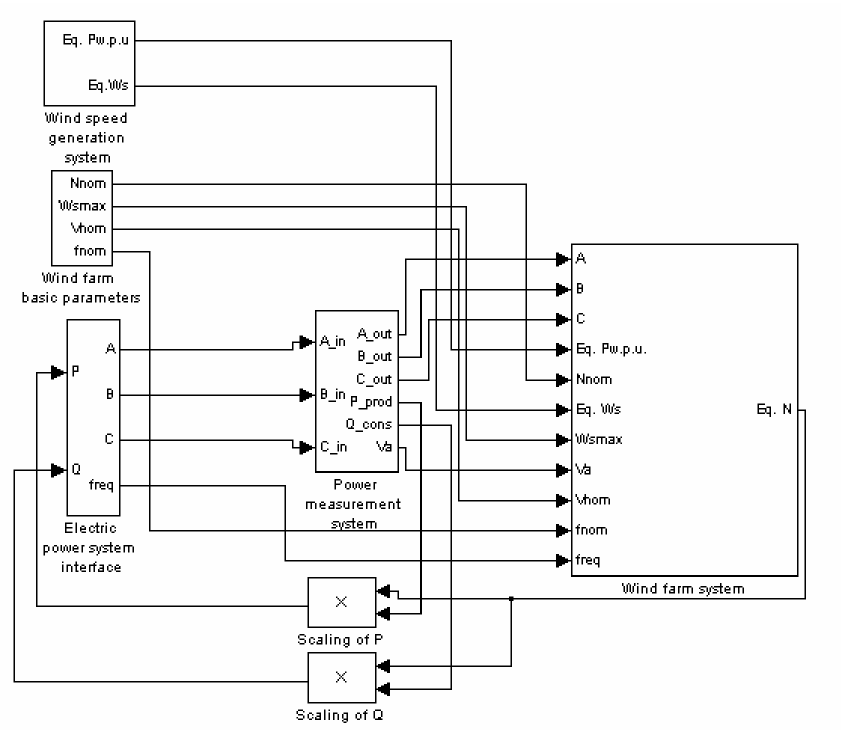

Fig. 34. Overall layout of wind farm model, as implemented in MATLAB/Simulink.

The basic parameters for the wind farm is set in the subsystem »***Wind farm basic parameters***« which is a passive subsystem, which simply provides data for the other subsystems. In this subsystem, the number of wind turbines in the wind farm, the maximum allowable operating wind speed for the wind turbines (which is normally around 25 m/s), the nominal voltage (in V RMS per phase) and the nominal frequency of the electric power system (in Hz) must be set, in order to make the other subsystems function properly.[25] This subsystem consists in a set of constants, and is shown in

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[24] The adapted demands to protection/control properties are based on the Danish common standards, i.e. the ELTRA specifications for larger wind farms and DEFU recommendations.

[25] Even though these parameters are set in this subsystem, the must however also be set in other parts of the subsystems, in specific system block's. This most unfortunate lack of integration is due to a lack of possibility to use normal dynamic variables in MATLAB/Simulink. Everywhere these parameters are to be set again it is mentioned in this model description.

Fig. 35. The data from this subsystem is fed into the subsystem »***Wind farm system***«, which is described later.

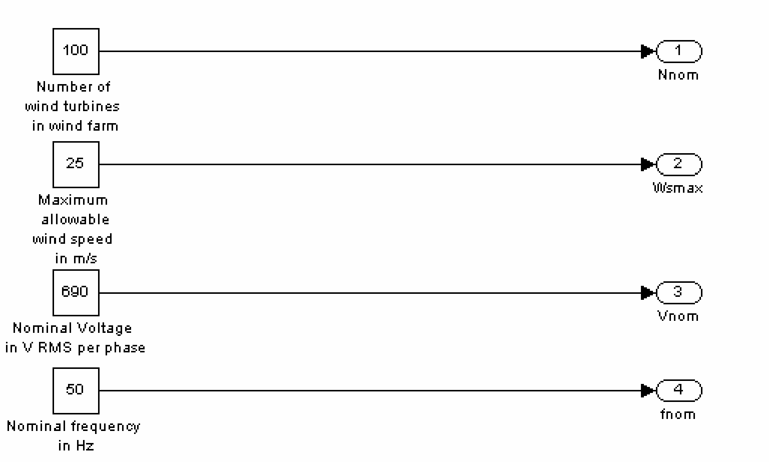

Fig. 35. Layout of the subsystem »Wind farm basic properties«; this subsystem consist of a set of constants, which are set, and is as such a passive subsystem. (The datavalues are sample data).

An equivalent wind speed is generated in the subsystem »***Wind speed generation system***«. This system provides an equivalent »p.u. power«-time series based on an equivalent single-wind turbine wind speed equivalent approach, which is also directly fed out to be used in other subsystems. This subsystem is detailed described in section H.2.3. The data from this subsystem is fed into the subsystem »***Wind farm system***«.

Data about the state of the adjacent electric power system is provided to the model from the subsystem »***Electric power system interface***«, which also return the wind farm model response to the adjacent electric power system. This subsystem can be made to interface with e.g. an ARISTO model or an electric power system model set up in MATLAB/Simulink. From the adjacent network, information about the actual voltage level and the frequency of the electric power system is provided, and converted into voltage/current signals for phases a, b and c (the output signals A, B and C). Furthermore, the fundamental frequency is separately fed out. These data are then supplied to the subsystem »***Wind farm system***«, some of them (the voltage/current signals) through a measurement subsystem, »***Power measurement system***« (which is described later). The model response on the wind speed and the electric power system state is then exchanged with the power system, as time series of the active power production and reactive power consumption (provided from the »***Power measurement system***«-subsystem).

The central part of the wind farm model is the subsystem »***Wind farm system***«, which on basis of input data regarding the wind farm basic parameters (supplied from the subsystem »***Wind farm basic parameters***«), the equivalent wind speed (i.e. both the equivalent wind farm wind speed and the equivalent wind power in p.u. supplied from the subsystem »***Wind speed generator system***«) and on the basis of the state of adjacent electric power system (provided from the »***Electric power system interface***«-subsystem, some data through the »***Power measurement system***«), calculates the wind farm response, both when it comes to response on electrical properties and when it comes to some of the more vital protection/control properties. The electrical behavior response is fed back through the phase wise data in the voltage/current lines A, B and C, whereas the protection/control response is supplied through an equivalent number of wind turbines that is actually in operation in the park. The »***Wind farm system***« is detailed described in section H.2.4.

To be able to feed back the active power and reactive power response as time series to the electric power system, a “measurement” system is needed. The measurement of the produced active power and the consumed reactive power is performed in the subsystem »***Power measurement system***«. This subsystem simultaneously measures the flowing current and voltage of each phase, and calculates the active and reactive power flow from the wind turbine, which is then supplied to the subsystem »***Electric power system interface***« as the wind farm response, after a scaling with the equivalent number of wind turbines in operation in the wind farm. Furthermore, it supplies the phase voltage which is fed to the »***Wind farm system***« for protection application. The measurement system in this subsystem is detailed described in H.2.5.

H.2.3. Wind speed generation system

The wind speed generation system consists of a two subsystems, one which constains a pre-generated time series of equivalent wind speed for a specific period of time, given the layout of the wind farm, and one which transforms the equivalent wind into an equivalent p.u.-power of the wind. The overall layout of the subsystem is shown in Fig. 36.

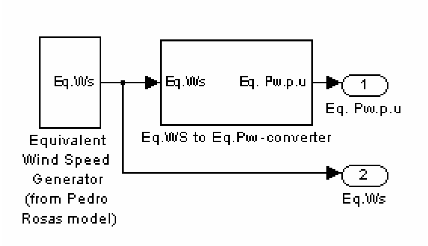

Fig. 36. Layout of »Wind speed generation system«.

The previously generated time series of equivalent wind speed is based on a previously published ph.d.-thesis, by Pedro Rosas [72], and demands knowledge of the layout of a wind farm, knowledge of the properties of the surroundings and knowledge of the approximate average level of the wind speed and wind direction . On this basis, an equivalent wind speed can be calculated, which takes into account the turbulence of the wind, caused by the wind turbulence itself, the turbulence caused by friction with the surroundings and turbulence from shadowing between wind turbines (including tower shadow).The subsystem »***Eq.WS to Eq.Pw-converter***« is simply a transformation from wind speed to output active power of a distinct wind turbine, based on the C_p-characteristics of the wind turbine. It consist of a »filter«, that transforms from Wind to power, and the signal from this filter is then, for compatibility reasons multiplied with (-1) to correct the power flow orientation. The subsystem is shown in Fig. 37.

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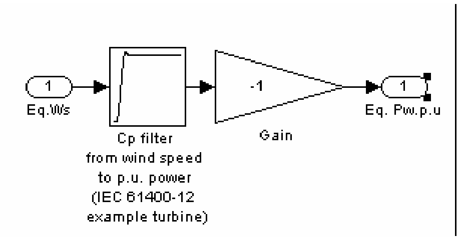


Fig. 37. Eq.WS to Eq.Pw-converter subsystem. The implemented C_p-filter is based on the sample wind turbine from IEC standard 61400-12, but any wind turbine system can be implemented.

H.2.4. Wind farm system

H.2.4.1. Overview of the subsystem

Modeling the wind farm electric response to the electric power system and the wind speed properties is the central part of the model. An overview of the wind farm system is shown in Fig. 38.

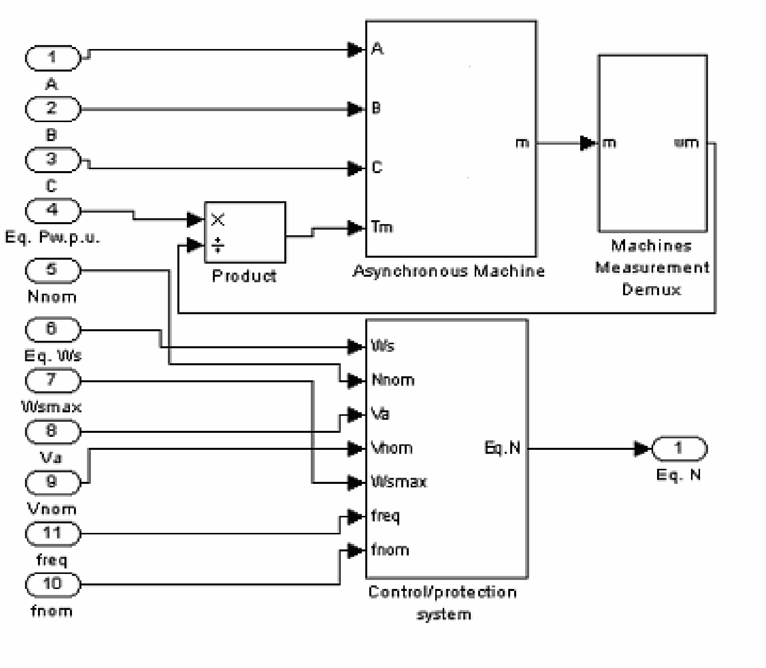


Fig. 38. Overview of wind farm system.

The wind farm system is based on a conventional asynchronous machine as wind turbine generator, which operates autonomously dependent on the electric power system status and on the equivalent wind power in p.u. (which is transformed into a p.u.-torque). The design is similar to the wind turbine system design denoted in section 2.1. In parallel a control/protection system, based on the Danish standards and recommendations from DEFU and ELTRA regarding larger wind turbines and wind farms connected to the transmission level electric power system.

An overview of the asynchronous machine model used for modeling the generator is shown in

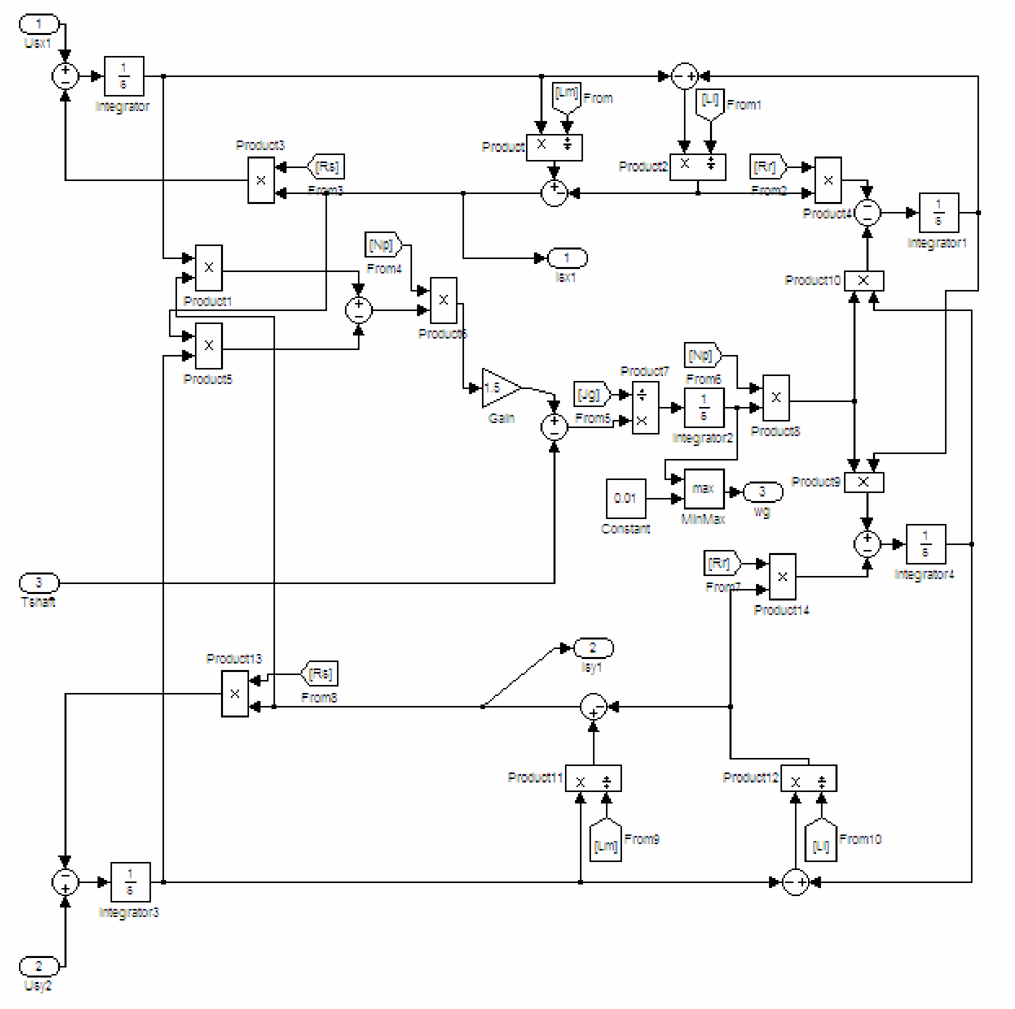


Fig. 39. Overview of the asynchronous generator model used for modeling the wind turbine generator.

H.2.4.2. The control/ protection system

H.2.4.2.1. Overview of the control/protection system

In order to make the wind farm model respond properly during a simulation, where stability is regarded, (at least) a minimum control/protection properties, that are demanded according to general specifications. As the western Danish electric power system is the most developed with respect to wind turbine and wind farm penetration, the system operator demands in this region may be reasonable to adapt in this model and are implemented, but as such, any kind of

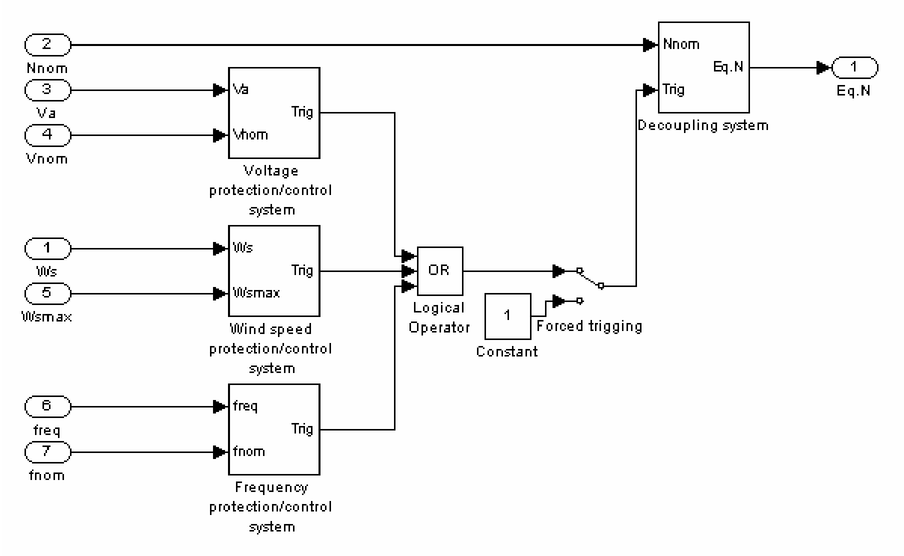


Fig. 40 Overview of control/protection system layout.

The principle behind the control/protection system is that it continuously performs check of whether or not certain operation parameters are within acceptable limits. In principle, any kind of control/protection criterion may be implemented, but to assure that the model is sufficiently fast, only three kinds of protection is implemented: Voltage proctection, wind speed protection and frequency protection. If any of these protection criterions are not fulfilled, a “trigger”-signal is set, intiating a disconnection process of wind turbines from the wind farm, resulting in a new number of wid turbines in the wind farm. Each of the subsystems are described below

H.2.4.2.2. Voltage protection system

The implemented voltage protection system is implemented to reflect the fundamental demands that DEFU recommends for wind turbines connected to the electric power system. The most adequate available recommendation from DEFU describes three criterions that wind turbines should fulfill when connected to an electric power system:

- Undervoltage: If the voltage level drops under 0.95 p.u. during 60 seconds, a wind turbine should disconnect from the electric power system
- Overvoltage 1: If the voltage level exceeds 1.1 p.u. during 60 seconds, a wind turbine should disconnect from the electric power system

- Overvoltage 2: If the voltage level exceeds more than 1.15 p.u. during more than 200 ms, a wind turbine should disconnect from the electric power system

The above given criterions are coherent with the ELTRA-demands for connection, which moreover demands that

- Undervoltage ELTRA: : If the voltage level drops under 0.8 p.u. during 2 seconds, a wind turbine should disconnect from the electric power system

These are implemented in the voltage protection system, which is shown below in Fig. 41

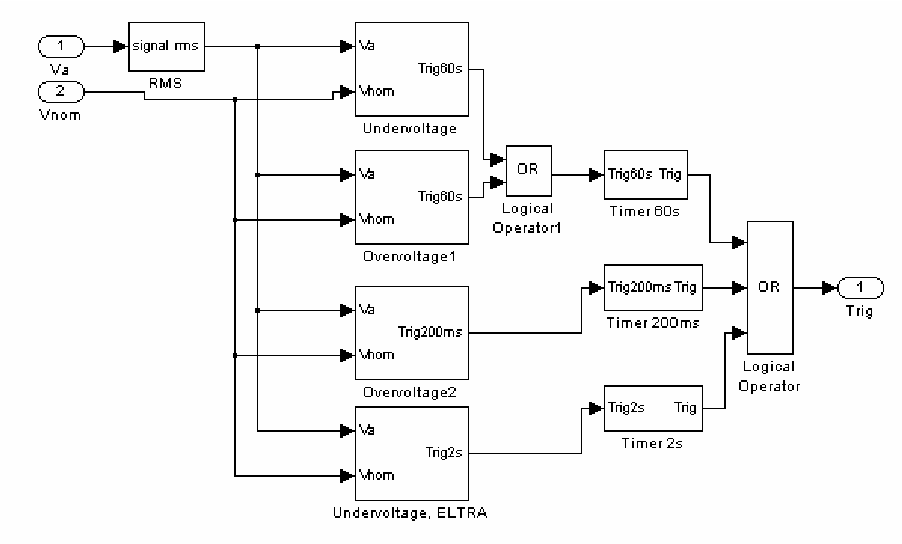


Fig. 41. Voltage protection system.

The implementation is set up in such a way that if one of the criterions for operation are nut fulfilled, it initiates a timer, with a proper time-delay property, and if then the operations criterions are still not fulfilled, a trigger signal is set, initiating the disconnection system.

H.2.4.2.3. Wind speed protection

For most kinds of wind turbines it applies, that they have a maximum allowable wind speed at which they operate. If the wind speed exceeds this level, they disconnect from the electric power system. This system is rather simple, as usually no time delay is given. The system is shown below in Fig. 42.

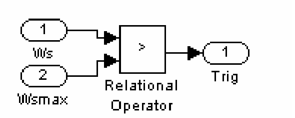


Fig. 42. Wind speed protection system.

The function of this system is, that if the maximum allowable wind speed is exceeded, the system sets a trigger signal, which initiates a disconnection process of wind turbines in the wind farm. If a time-delay is implemented in a distinct wind turbine, this can of course also be implemented.

H.2.4.2.4. Frequency protection system

An overview of the frequency protection system is shown below in Fig. 43

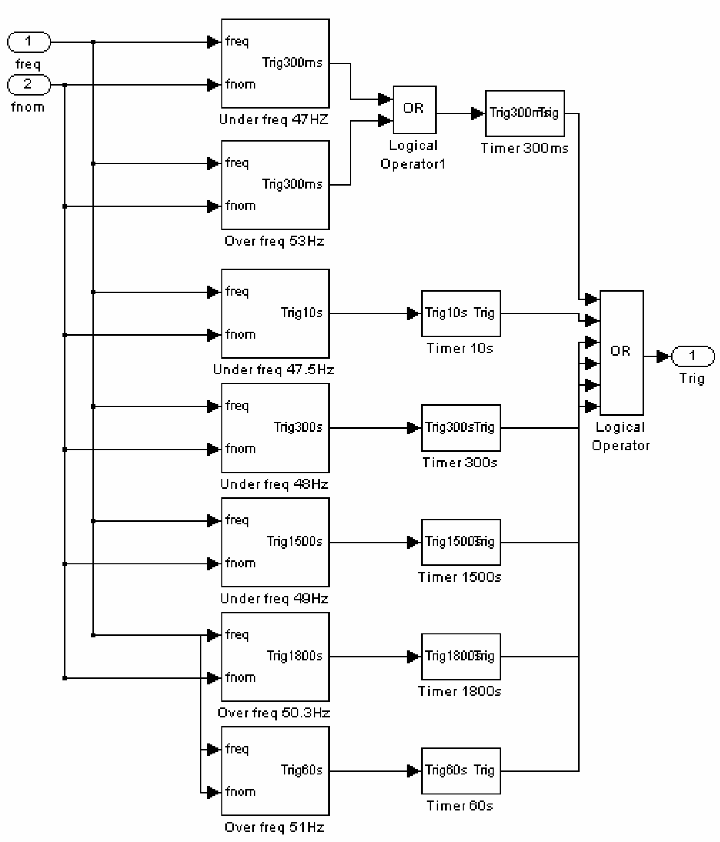


Fig. 43. Frequency protection system.

The criterions are based on the ELTRA-specification for wind farms connected to the transmission grid, which are shown in Table 1.

Under frequencies	– At frequencies below 47.0 Hz, a wind turbine should disconnect after 0.3 sec. – At frequencies below 47.5 Hz, a wind turbine should disconnect after 10 sec. – At frequencies below 48.0 Hz, a wind turbine should disconnect after 5 minutes. – At frequencies below 49.0 Hz, a wind turbine should disconnect after 25 minutes.
Over frequencies	– At frequencies exceeding 53.0 Hz, a wind turbine should disconnect after 0.3 sec. – At frequencies exceeding 51.0 Hz, a wind turbine should disconnect after 1 minute. – At frequencies exceeding 50.3 Hz, a wind turbine should disconnect after 30 minutes.

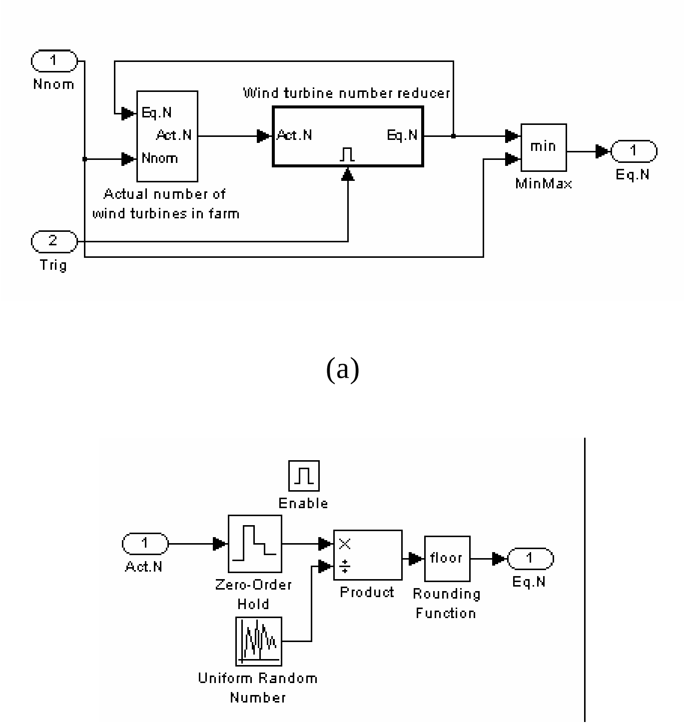
Table 1. ELTRA-specification regarding frequency-shedding of wind turbines.

H.2.4.2.5. Disconnection system

If any of the protection systems set a trigger signal, a disconnection of wind turbines in the wind farm should occur, resulting in less connected wind turbines, and therefore a reduces number of wind turbines.

The disconnection of wind turbines will not occur simultaneously for all wind turbines in a wind farm – some will disconnect before others. In the ELTRA-reccommendation, it is actually set up as a demand that the disconnetion does not occur simultaneously. Thus, it must be considered reasonable to model the disconnection of wind turbines as a stochastic process, after which the equivalent number of wind turbines in the wind farm is reduced.

The disconnection system is shown in Fig. 44. The subsystem operates when a trigger signal from one of the protection systems are set, indicating that one of the operational criterions are not properly fulfilled. Thus, if the trigger is set, the subsystem initiates a stochastical reduction of the number of wind turbines, by generating a random number, which is divided into the actual number of operating wind turbines in the wind farm. This stochastic process has its parameters set in such a manner that e.g. a wind farm of approx. 100 wind turbines is fully disconnected after approx. 10 sec.



(a)

(b)

Fig. 44. Disconnection system; (a) shows the overall layout of the disconnection system, in which the number of equivalent wind turbines in the farm is reduced, (b) shows the wind turbine number-reducer subsystem, which involves a stochastic reduction of the number of wind turbines.

H.2.5. Power Measurement system

The output of the wind farm model system to an electric power system model is the resulting flow of active and reactive power from the wind turbine system. To detect and calculated this, the model is in need of a "measurement system", which gives time series of active and reactive power flow from the wind turbine system.

The measurement system is modeled using subsystems from MATLAB/Simulink's PowerSystem Blockset, and is shown in Fig. 45.

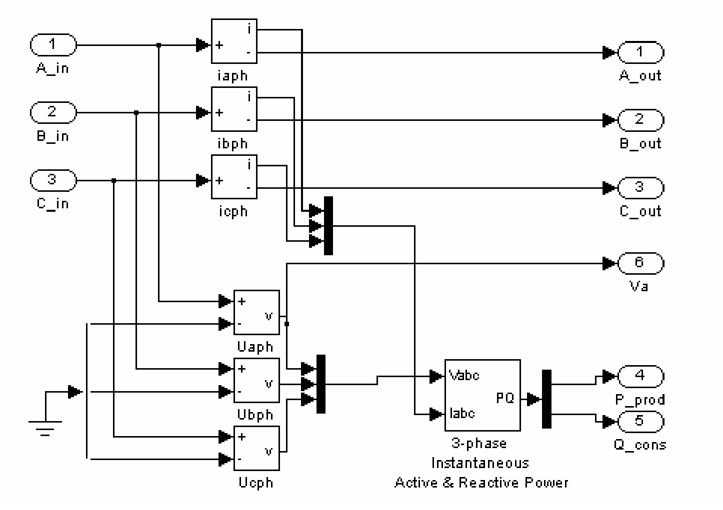


Fig. 45. The power measurement subsystem.

APPENDIX I : THE MODEL FOR CHP-PLANTS

I.1. Model demands and requirements

A part of the study involves the investigation of the impact of introducing non-dispatchable CHP-plants in an electric power system together with wind power. It is needed to have the model built up in a manner that reflects the investigations that are to be made.

The model for CHP-plants is mainly to be used in relation to the large-scale simulations, where the the focus is to investigate the CHP-plant behavior when it comes to voltage stability, power oscillations and synchronous stability. The model should reflect behavior under normal operation conditions as well as under more transient conditions, such as fault situations.

As these investigations are to be made in the ARISTO-system, the model should be fully compatible with ARISTO.

I.2. Model description

I.2.1. Model overview

As discussed in section 2.1.5, a CHP-plant can to a certain extend be regarded as a small-scale »regular« power plant with a special mode of operation, usually operated in »on/off«-mode (i.e. either operating at full production or not producing at all) autonomously. Usually, they produce at $\cos(\varphi) = 1$.

Given these facts, the modelling in ARISTO is straight-forward, as it can be modeled as a regular power plant by simply applying data from a CHP-plant. Thus, the model is implemented directly in ARISTO, using data from a representative CHP-plant, for which data is provided from ELTRA

I.2.2. Data for CHP-plant

Two available data sets are provided from ELTRA. Both are given below in the following sections

I.2.2.1. CHP-Plant data no. 1

I.2.2.1.1. Two-winding Step-Up Transformer Data Form for CHP-plant no.1

Plant: No.1.	Item: Step-Up Transformer
Manufacturer: Trafo-Union	Type: TWSN 7548 / FTNR N 421 588
	Date / Signature: 31.01.2003/PLU

Parameter	**Unit**	**Description**	**Value**
S_n	[MVA]	Nominal three-phase apparent power	35,0
U_{n1}	[kV]	Nominal phase-phase voltage, primary side	63,0
U_{n2}	[kV]	Nominal phase-phase voltage, secondary side	10,5
Vector group	-	Vector group / connection, e.g. Dyn11	Yd11
Tap side	-	Tap changer at side (Please mark appropriate box)	■ Primary ☐ Secondary
du_{tp}	[%/tap]	Tap changer: additional voltage per tap	2,0
n_{tpmin}	-	Tap changer: minimum position	1
n_{tpmax}	-	Tap changer: maximum position	14
n_{tp0}	-	Tap changer: neutral position	4
u_k	[%]	Positive sequence short circuit voltage	12,06
P_{cu}	[kW]	Copper losses	94,79
I_0	[%]	No load excitation current	0,06
P_0	[kW]	No load losses (iron losses)	18,42

I.2.2.1.2. Synchronous Machine Data Form for CHP-plant no.1

Plant:	Item: Synchronous Generator
Manufacturer: GEC-Alstom	Type: AG 204 M 185
	Serial No.: F21123601
	Date / Signature: 03.04.2003/PLU

Parameter	**Unit**	**Description**	**Value**
U_n	[kV]	Nominal phase-phase voltage	10,5
S_n	[MVA]	Nominal three-phase apparent power	35,812
f_n	[Hz]	Nominal frequency	50
cosφ	-	Nominal power factor	0,85
J_{tot}	[kg m^2]	Total moment of inertia of generator rotor, prime mover, gear box etc. referred to generator speed	2725
N_{pp}	-	Number of pole pairs	2
n_n	[rpm]	Nominal speed	1500
X_d	[p.u.]	Synchronous reactance d-axis, unsaturated	1,92
X'_d	[p.u.]	Transient reactance d-axis, unsaturated	0,235
X''_d	[p.u.]	Subtransient reactance d-axis, unsaturated	0,175
X_q	[p.u.]	Synchronous reactance q-axis, unsaturated	0,99
X''_q	[p.u.]	Subtransient reactance q-axis, unsaturated	0,32
T'_{d0}	[s]	Transient open circuit time constant d-axis	9,0
T''_{d0}	[s]	Subtransient open circuit time constant d-axis	0,03
T''_{q0}	[s]	Subtransient open circuit time constant q-axis	0,07
R_s	[p.u.]	Stator resistance	0,0028
X_l	[p.u.]	Stator leakage reactance	0,109
$SG_{1.0}$	[p.u.]	Saturation point at 1.0 p.u. voltage	0,1354

$SG_{1.2}$	[p.u.]	Saturation point at 1.2 p.u. voltage	0,5885
X_2	[p.u.]	Negative sequence reactance	0,191
X_0	[p.u.]	Zero sequence reactance	0,10
Rotor type	-	Type of rotor (Please mark appropriate box)	■ Salient pole ☐ Round rotor
$X_{d,sat}$	[p.u.]	Saturated synchronous reactance	1,824
$X''_{d,sat}$	[p.u.]	Saturated subtransient reactance	0,163

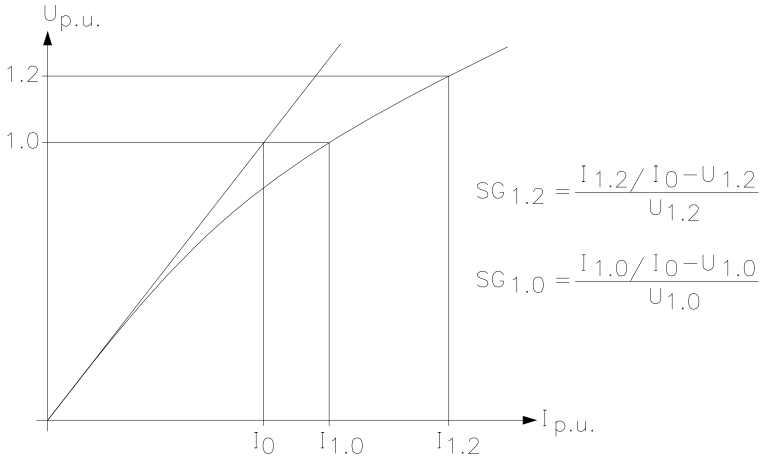


Fig. 46. Definition of generator saturation points SG1.0 and SG1.2 for CHP-plant no.1.

I.2.2.1.3. Voltage Regulator, Excitation System and Power System Stabiliser Data Form for CHP-plant no.1

Plant:

Item: Synchronous Generator AVR+PSS

Manufacturer: GEC Alsthom

Type: ______________________________

Date / Signature: 31.01.2003/PLU

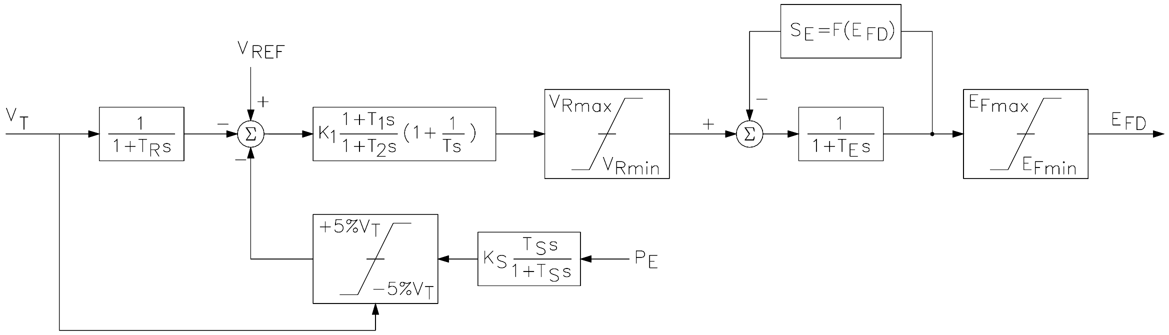


Fig. 47. Voltage regulator and exitation system for CHP-plant no.1.

Parameter	**Unit**	**Description**	**Value**
T_R	[sec]	Voltage detection time constant	0,02
K_1	[pu]	Regulator gain	39,2
T_1	[sec]	Regulator lead-lag filter lead time constant	0,3
T_2	[sec]	Regulator lead-lag filter lag time constant	0,03
T	[sec]	Regulator integrator time constant	5
V_{Rmax}	[pu]	Regulator max limit	6,1
V_{Rmin}	[pu]	Regulator min limit	-5,2
T_E	[sec]	Exciter time constant	0,8
E_{FEmax}	[pu]	Exciter field voltage max limit	6,15
$E_{FE\ 0,75\ max}$	[pu]	Exciter field voltage at 75 % max limit	4,6125
S_{Emax}	[pu]	Exciter saturation factor at E_{FEmax}	1,48
$S_{E\ 0,75\ max}$	[pu]	Exciter saturation factor at $E_{FE\ 0,75\ max}$	1,33
E_{Fmax}	[pu]	Generator field voltage max limit	7,2
E_{Fmin}	[pu]	Generator field voltage min limit	0,0
K_S	[pu]	Stabiliser gain	1,0

T_S	[sec]	Stabiliser wash-out filter time constant	1,0

I.2.2.1.4. Speed Governing System Data Form for CHP-plant no.1

Plant: Item: Steam Turbine SGS

Manufacturer: ______________________ Type: ______________________________

Date / Signature: 31.01.2003/PLU

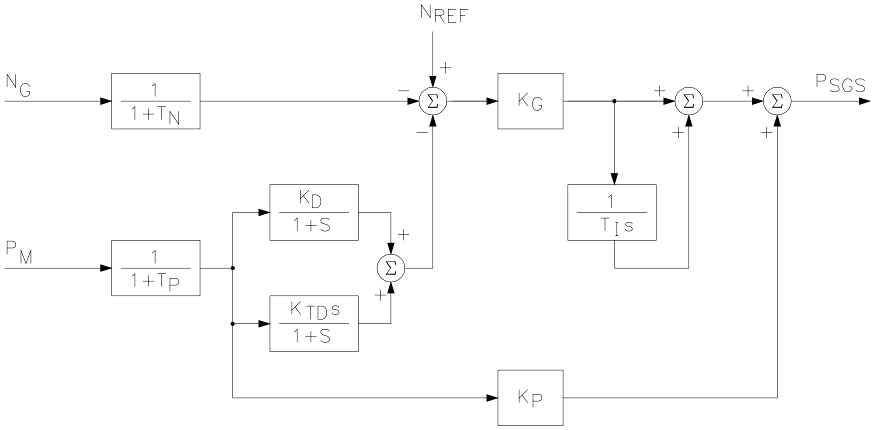


Fig. 48. Speed governing system for CHP-plant no.1.

Parameter	Unit	Description	Value
T_N	[sec]	Speed detection time constant	0,003
K_G	[pu]	Speed governor gain	20
T_I	[sec]	Speed governor integrator time constant	1,0
T_P	[sec]	Power detection time constant	0,0019
K_D	[pu]	Droop coefficient	0,04
K_{TD}	[pu]	Transient droop coefficient	0,015
K_P	[pu]	Power feed-forward gain	0,7

I.2.2.1.5. Prime Mover Data Form for CHP-plant no.1

Plant: Item: Steam Turbine PM

Manufacturer: ______________________ Type: ______________________________

Date / Signature: 31.01.2003/PLU

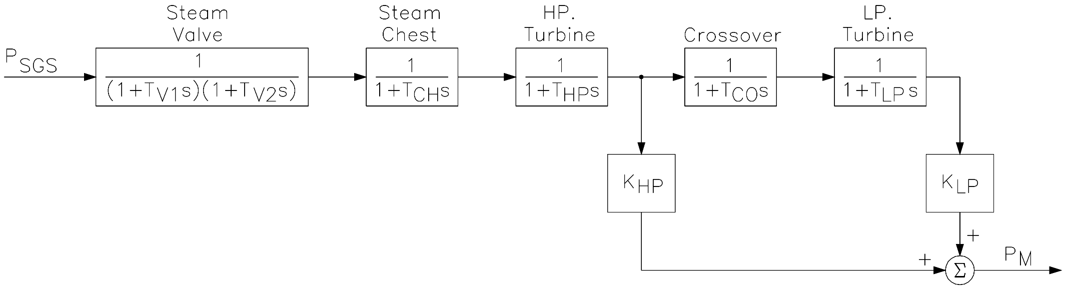


Fig. 49. Prime mover system for CHP-plant no.1.

Parameter	**Unit**	**Description**	**Value**
T_{V1}	[sec]	Steam valve el/hydr converter time constant	0,03
T_{V2}	[sec]	Steam valve main time constant	0,08
T_{CH}	[sec]	Steam chest time constant	0,085

I.2.2.2. CHP-plant data no.2

I.2.2.2.1. Two-winding Step-Up Transformer Data Form for CHP-plant no.2.

Plant: Item: Step-Up Transformer

Manufacturer: Smit Type: GSU

Smit Ref. No.: 102.30.1.5640

Date / Signature: 31.03.2003/PLU

Parameter	**Unit**	**Description**	**Value**
S_n	[MVA]	Nominal three-phase apparent power	70,0
U_{n1}	[kV]	Nominal phase-phase voltage, primary side	69,19
U_{n2}	[kV]	Nominal phase-phase voltage, secondary side	10,5
Vector group	-	Vector group / connection, e.g. Dyn11	YNd11
Tap side	-	Tap changer at side (Please mark appropriate box)	No tap changer
u_k	[%]	Positive sequence short circuit voltage	12,29
P_{cu}	[kW]	Copper losses	172,7
u_{k0}	[%]	Zero sequence short circuit voltage	11,79
u_{kr0}	[%]	Zero sequence resistive short circuit voltage	0,32
I_0	[%]	No load excitation current	0,079
P_0	[kW]	No load losses (iron losses)	29,3

I.2.2.2.2. Synchronous Machine Data Form for CHP-plant no.2.

Plant: Item: Synchronous Generator

Manufacturer: Brush Electrical Machines Type: BDAX 72.340 PRH

Serial No.: 62042A-1G

Date / Signature: 03.04.2003/PLU

Parameter	**Unit**	**Description**	**Value**
U_n	[kV]	Nominal phase-phase voltage	10,5
S_n	[MVA]	Nominal three-phase apparent power	69,412
f_n	[Hz]	Nominal frequency	50
cosφ	-	Nominal power factor	0,85

J_{tot}	[kg m^2]	Total moment of inertia of generator rotor, prime mover, gear box etc. referred to generator speed	5483
N_{pp}	-	Number of pole pairs	1
n_n	[rpm]	Nominal speed	3000
X_d	[p.u.]	Synchronous reactance d-axis, unsaturated	2,50
X'_d	[p.u.]	Transient reactance d-axis, unsaturated	0,25
X''_d	[p.u.]	Subtransient reactance d-axis, unsaturated	0,18
X_q	[p.u.]	Synchronous reactance q-axis, unsaturated	2,29
X'_q	[p.u.]	Transient reactance q-axis, unsaturated	0,31
X''_q	[p.u.]	Subtransient reactance q-axis, unsaturated	0,22
T'_{d0}	[s]	Transient open circuit time constant d-axis	9,4
T''_{d0}	[s]	Subtransient open circuit time constant d-axis	0,055
T'_{q0}	[s]	Transient open circuit time constant q-axis	2,9
T''_{q0}	[s]	Subtransient open circuit time constant q-axis	0,065
R_s	[p.u.]	Stator resistance	0,002
X_l	[p.u.]	Stator leakage reactance	0,11
$SG_{1.0}$	[p.u.]	Saturation point at 1.0 p.u. voltage	0,081
$SG_{1.2}$	[p.u.]	Saturation point at 1.2 p.u. voltage	0,351
X_2	[p.u.]	Negative sequence reactance	0,196
X_0	[p.u.]	Zero sequence reactance	0,083
Rotor type	-	Type of rotor (Please mark appropriate box)	☐ Salient pole ■ Round rotor
$X_{d,sat}$	[p.u.]	Saturated synchronous reactance	2,025
$X''_{d,sat}$	[p.u.]	Saturated subtransient reactance	0,146

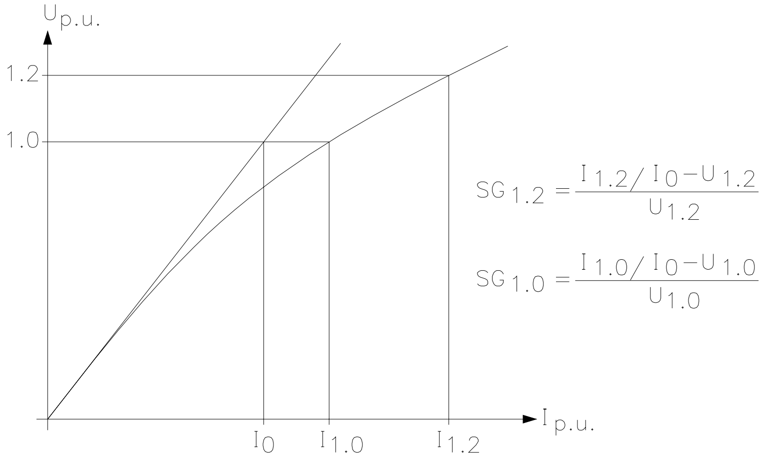


Fig. 50. Definition of generator saturation points SG1.0 and SG1.2 for CHP-plant no.2.

I.2.2.2.3. Voltage Regulator and Excitation System Data Form for CHP-plant no.2

Plant: Item: Synchronous Generator AVR

Manufacturer: Brush Electrical Machines Type: ________________________________

Date / Signature: 31.03.2003/PLU

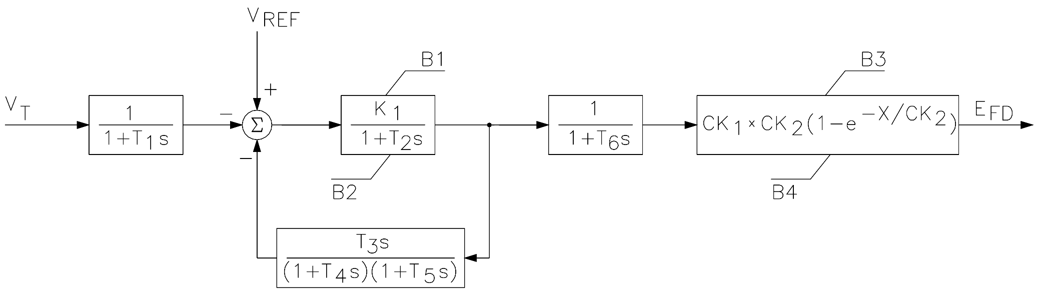


Fig. 51. Voltage regulator and exitation system for CHP-Plant no.2.

Parameter	Unit	Description	Value
T_1	[sec]	Voltage detection time constant	0,022
K_1	[pu]	Regulator gain	1000
T_2	[sec]	Regulator time constant	0,1
B_1	[pu]	Regulator anti wind-up max limit	15

B_2	[pu]	Regulator anti wind-up min limit	-15
T_3	[sec]	Regulator feed-back time constant	0,031
T_4	[sec]	Regulator feed-back time constant	0,6
T_5	[sec]	Regulator feed-back time constant	1,3
T_6	[sec]	Exciter time constant	1,3
CK_1	[pu]	Exciter adjustment parameter	1
CK_2	[pu]	Exciter adjustment parameter	10
B_3	[pu]	Exciter anti wind-up max limit	6,0
B_4	[pu]	Exciter anti wind-up min limit	0,0

I.2.2.2.4. Speed Governing System Data Form for CHP-plant no.2.

Plant: Item: Steam Turbine SGS

Manufacturer: Thomassen International Type:

Date / Signature: 31.03.2003/PLU

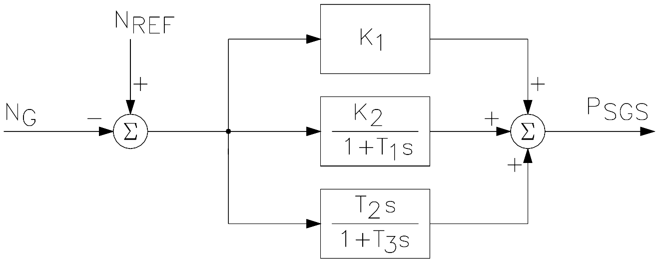


Fig. 52. Speed governing system for CHP-plant no.2.

Parameter	Unit	Description	Value
K_1	[pu]	Governor proportional gain	0,0
K_2	[pu]	Governor integrator gain gain	25
T_1	[sec]	Governor integrator time constant	0,05
T_2	[sec]	Governor differentiator time constant	0,0
T_3	[sec]	Governor differentiator smoothing time constant	0,5

I.2.2.2.5. Prime Mover and Steam Valves Data Form for CHP-Plant no.2.

Plant:
Item: Steam Turbine PM

Manufacturer: Thomassen International
Type: ______________________________

Date / Signature: 31.03.2003/PLU

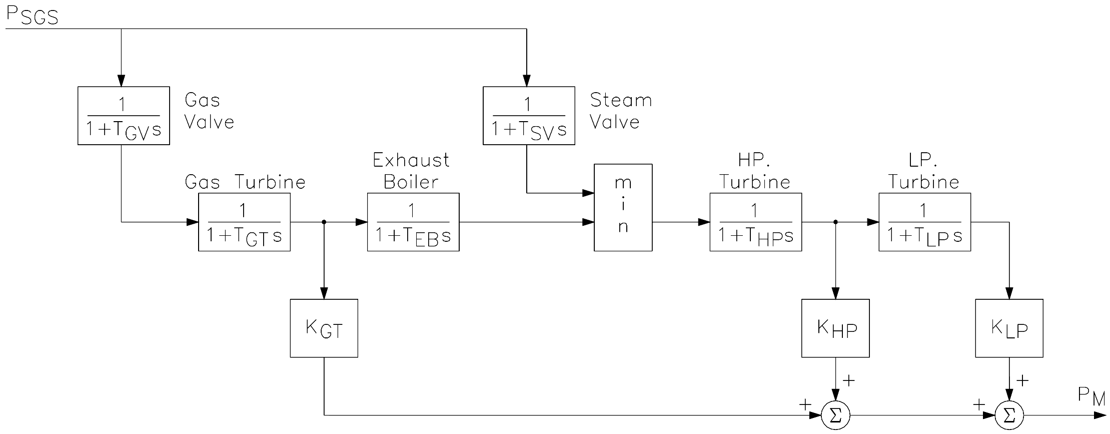


Fig. 53. Prime mover system CHP-plant no.2.

Parameter	Unit	Description	Value
T_{GV}	[sec]	Gas turbine fuel valve time constant	0,1
T_{GT}	[sec]	Gas turbine time constant	1,0
T_{EB}	[sec]	Exhaust boiler time constant	5,0

T_{SV}	[sec]	Steam turbine live steam valve time constant	0,075
T_{HP}	[sec]	High pressure steam turbine time constant	0,20
T_{LP}	[sec]	Low pressure steam turbine time constant	0,15
K_{GT}	[sec]	Gas turbine power fraction[26]	0,71
K_{HP}	[sec]	High pressure turbine power fraction[1]	0,21
K_{LP}	[sec]	Low pressure turbine power fraction[1]	0,08

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[26] Please notice $K_{GT} + K_{HP} + K_{LP} = 1,0$

APPENDIX J : SHORT ON ARISTO AND THE ARISTO SYSTEM

J.1. ARISTO – real time power system simulation

J.1.1. Short on the history of ARISTO

Many of the simulations in this thesis has been performed in the ARISTO (Advanced Real-time Interactive Simulator for Training and Operation) environment, which is a power system simulation environment, that simulates electric power systems in real time, regareded as positive sequence systems. The ARISTO system has been developed by ABB Automation Systems AB and Svenska Kraftnät (the Swedish ISO) on basis of more than 15 years of development, and is still continuously being enhanced.

During the 80’s Svenska Kraftnät identified the lack of a training simulator.Consequently, a research project was initiated at Royal Institute of Technology in Stockholm, Sweden, in 1985. The main objective was to find a method that would allow real-time simulation of power system dynamics covering transient stability phenomena as well as slow dynamics such as voltage collapse and restoration procedures. Prototypeing proved that objectives were achievable. A product development program was initiated aimed at creating a simulator for Svenska Kraftnät based on the research results.

In view of the successful progress of this program, Svenska Kraftnät decided in 1991 to expand the scope to include the development of a commercial version of the simulator to be offered to the power industry.

To be able to fulfill such a goal a strategic alliance, based on a joint venture arrangement, was agreed upon between Svenska Kraftnät, ABB Automation Systems AB and CAP in May 1993. At the same time, the Svenska Kraftnät version was installed at the operation facilities of Svenska Kraftnät.

J.1.2. Philosophy and capabilities

The philosophy behind the development of the ARISTO environment is to provide a multipurpose simulation tool that can be used for both advanced dynamic simulation studies and training op system operators in electric power systems, but doing it fully interactive and in real time. Traditionally, these tasks has been done in different environments, but are with the ARISTO-environment combined in one.

The time and frequency domain covered by the ARISTO simulation technique can be used to illustrate the various phenomena it is possible to continously simulate in real time for several hundreds of nodes. An overview of the simulator capabilities is shown in Fig. 54. As it can be seen, the ARISTO-environment operates within a time phrame from approx. 0.1 sec and above, covering the more classical power system phenomenas, that are dealt with in static and dynamic operation and control-studies. This fact means for instance that ARISTO well serve needs to analyze dynamics that incorporate both transient stability as well as slow dynamics, such as voltage collapse and restoration procedures, or power system oscillations within larger power systems, whereas it is not as well suited for analysing faster phenomenas such as harmonics, sub-synchronous studies of electric power generators, etc.

Power system studies that may be performed in ARISTO are

- Transient stability
- Voltage stability and voltage collapse
- Long term dynamics
- Island operation
- Planning and testing of procedures, e.g. operation schemes

Simulating in real-time, in stead of off-line, in an interactive environment visualizes the actual behavior of the electric power system, and hereby makes the user able of studying any simulation case as it happens. This can be of value in for both research and training applications.

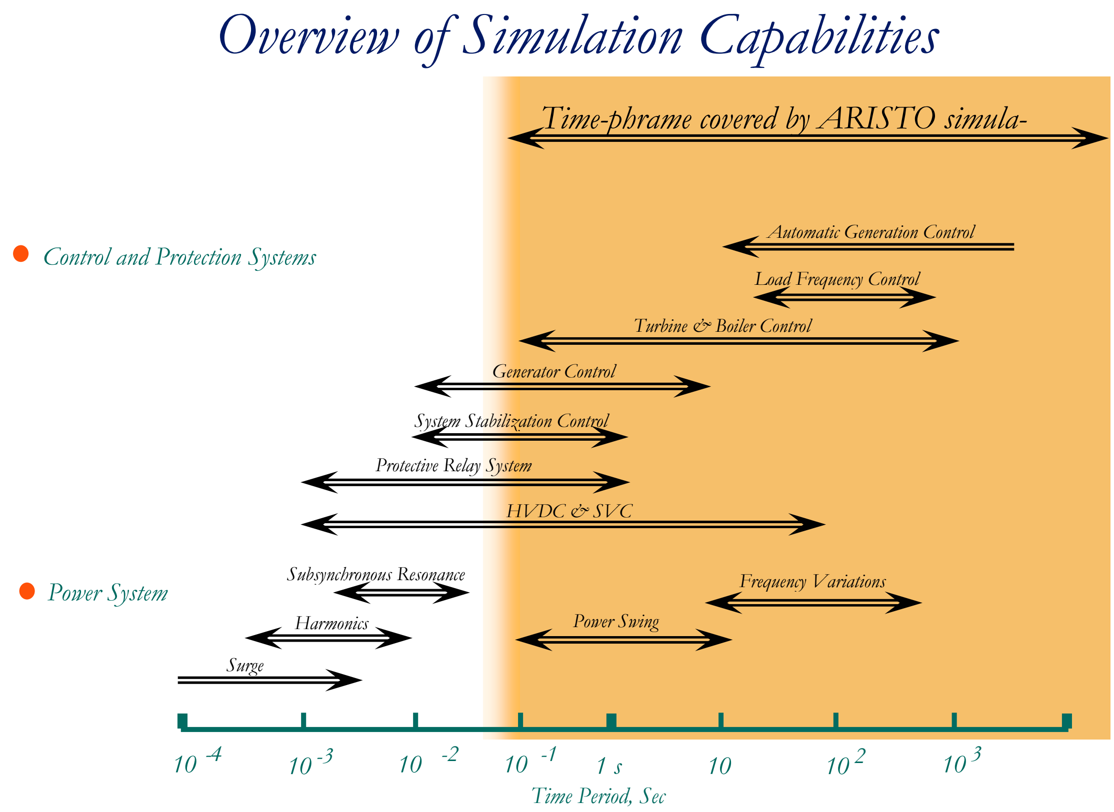

Fig. 54. Time and frequency domain covered by simulations in the the ARISTO-environment.

However, there are limitations to the use of ARISTO. Among these are the lack of possibility to investigate asymmetric contingencies, the use of HVDC-equipment and smaller problems like e.g. lack of direct representation of transformers with more than two windings.

The ARISTO-system consists of a set of tightly coupled programs, which use is basically coupled by the use of a common interface and sharing of data resources.

J.2. ARISTO value proposition

What distinguishes ARISTO from other simulation tools are mainly 3 features

- Real-time simulation capability for power system analysis: Conducting power system analysis in real time adds value by giving the analyst a closer feel of the dynamic behavior of the power system. Being able to see occurrences as they happen opens up for (1) better interaction with the simulation tool, and (2) identfying issues that would have been hard to see using a traditional simulation tool, where the outputs is a set of data series

- “Close-to real“ graphical interface: Having a graphical interface that shows the simulation results both as an interactive power system network and the more traditional time series outputs allows for easier interpretation of the simulation results. Easier interpretation enables analysts to easier identification of issues. This opens up for top-down research with a issue driven problem solving approach – where the focus of the research effort is focused around solving the immediate issues that can be identified – compared to more traditional bottom-up research with a topic driven problem solving approach – where a set of properties are investigated, and then the overall impact is assessed by scaling up. It is the hypothesis that the value and impact of top-down research is higher than bottom up reseach as the top down approach focuses on the most prominent issues, whereas bottom up focuses on topics regardsless of their impact potential.
- Common plat form for research and training: Providing a common platform for reseach and training makes the link between research and application of the research results closer, and therefore the likeliness of impact higher. From a value perspective, high quality reseach is worthless if the results are never applied.

I

APPENDIX K : TABELS SUMMING UP SIMULATION RESULTS

K.1. Tables showing results of simulations under stable conditions

K.1.1. Simulation results in the Nordic 32 test system

Power system model	Simulation study	Short on the study	Observations
Simulations in Nordic 32 test system with 100 % wind turbines replacing Barsebäck	Response with stable wind conditions (reference study)	1500 MW wind farms installed in Southern Sweden (100% wind case) Wind blowing with a mean speed of 8 m/s	The operation is stable; there are no observed stability problems, neither with respect to active or reactive power balance. Some variations in the active power production from the wind turbine oscillate back and forth, but they are small, and not oscillating with frequencies that trig the power system oscillation modes.
	Response with wind blow up	As the reference study, but with an increase in wind speed of from 8 m/s to 18 m/s over 100 s	The operation is stable until wind begins to blow up. As wind starts to blow up, the active power produced is increased and the reactive power consumption. Active power stability is maintained as in the reference study throughout wind blowout, whereas reactive power balance in the southern Swedish electric power system can not be maintained, and ultimately the voltage collapses in the southern Swedish electric power system after approx. 110 s.
	Response with wind blow down	As the reference study, but with a wind speed decrease from 8 m/s to 0 m/s over 100s	The operation is initially stable. As the wind speed decreases, the active power production decreases accordingly, but the production in the mid and northern parts of the Swedish electric power system compensates by increasing production. Active power balance is maintained as in the reference study. As the wind speed decreases, the reactive power consumption decreases, and the voltage is slightly increased. Operation is stable after the wind speed has decreased fully.

Power system model	Simulation study	Short on the study	Observations
Simulations in Nordic 32 test system with 50 % wind turbines and 50% CHP replacing Barsebäck	Response with stable wind conditions (reference study)	750 MW wind farms and 375 MW CHP installed in Southern Sweden (50% wind case) Wind blowing with a mean speed of 8 m/s	The operation is stable; there are no observed stability problems, neither with respect to active or reactive power balance. Some variations in the active power production from the wind turbine oscillate back and forth, but they are small, and not oscillating with frequencies that trig the power system oscillation modes. (Voltage level is slightly higher than in the 100% wind case; the small power system oscillations are smaller than the 100% wind turbine case)
	Response with wind blow up	As the reference study, but with an increase in wind speed of from 8 m/s to 18 m/s over 100 s	The operation is stable until wind begins to blow up. As wind starts to blow up, the active power produced is increased and the reactive power consumption. Active power stability is maintained as in the reference study throughout wind blowout, whereas reactive power balance in the southern Swedish electric power system is stressed, (but not as hard as in the 100% wind case). The long term voltage stability is maintained, but the voltage is lower than before the blow up. Still, the voltage is kept over 360 (- 10% of rated voltage).
	Response with wind blow down	As the reference study, but with a wind speed decrease from 8 m/s to 0 m/s over 100s	The operation is initially stable. As the wind speed decreases, the active power production decreases accordingly, but the production in the mid and northern parts of the Swedish electric power system compensates by increasing production. Active power balance is maintained as in the reference study. As the wind speed decreases, the reactive power consumption decreases, and the voltage is slightly increased (but not as much as in the 100% wind case). Operation is stable after the wind speed has decreased fully.

K.1.2. Simulation results in the Sydkraft test system

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 100 % wind turbines near Barsebäck	Response with stable wind conditions (reference study)	500 MW wind farms installed and connected to Barsebäck through either the 130kV or the 400 kV busbar (both studies are made) Wind blowing with a mean speed of 8 m/s	The operation is stable; there are no observed stability problems, neither with respect to active or reactive power balance, and regardless of the voltage level at which the wind farm is connected. Some variations in the active power production from the wind turbine oscillate back and forth, but they are small, and not oscillating with frequencies that trig the power system oscillation modes.
	Response with wind blow up	As the reference study, but with an increase in wind speed of from 8 m/s to 18 m/s over 100 s	Connected to 130 kV: Active power balance is maintained throughout the blow up. The voltage profile for the neighbouring electric power systems is highly affected, due to reactive power imbalance caused by the increased reactive power consumption of the wind turbines. After approx. 80 s the Barsebäck region suffer from undervoltage problems, especially on 130 kV level, and after approx. 110 s the Barsebäck 130 kV substation suffer from voltage collapse. Connected on 400 kV: Active power balance is maintained throughout the blow up. The voltage profile for the neighbouring electric power systems is highly affected (but not as bad as in the 130kV study), due to reactive power imbalance caused by the increased reactive power consumption of the wind turbines. After approx. 120 s the Barsebäck region suffer from undervoltage problems, especially on 130 kV level, but voltage collapse does not occur.
	Response with wind blow down	As the reference study, but with a wind speed decrease from 8 m/s to 0 m/s over 100s	Connected to 130 kV: Active power balance is maintained throughout the blow down. When the blow down occurs, the voltage profile is stable, though with locally small voltage increases. After the wind speed has decreased both active and reactive power balance is maintained, and operations are steady. Connected on 400 kV: Active power balance is maintained throughout the blow down. When the blow down occurs, the voltage profile is stable, though with locally slight voltage increases (increases are smaller than when connected to 130 kV). After the wind speed has decreased both active and reactive power balance is maintained, and operations are steady.

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 100 % wind turbines near Gothemburg	Response with stable wind conditions (reference study)	500 MW wind farms installed and connected to Gothemburg through the 400 kV busbar in the Gothemburg equivalent. Wind blowing with a mean speed of 8 m/s	The operation is stable; there are no observed stability problems, neither with respect to active or reactive power balance, and regardless of the voltage level at which the wind farm is connected. Some variations in the active power production from the wind turbine oscillate back and forth, but they are small, and not oscillating with frequencies that trig the power system oscillation modes.
	Response with wind blow up	As the reference study, but with an increase in wind speed of from 8 m/s to 18 m/s over 100 s	Active power balance is maintained throughout the blow up. The voltage profile for the neighbouring electric power systems is highly affected, due to reactive power imbalance caused by the increased reactive power consumption of the wind turbines. After approx. 120 s the Gothemburg region suffers from under voltage problems, and the general voltage profile in all of the southern Swedish electric power system is affected, but voltage collapse does not occur.
	Response with wind blow down	As the reference study, but with a wind speed decrease from 8 m/s to 0 m/s over 100s	Active power balance is maintained throughout the blow down. When the blow down occurs, the voltage profile is stable, though with locally slight voltage increases. After the wind speed has decreased both active and reactive power balance is maintained, and operations are steady.

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 100 % wind turbines near Karlshamn	Response with stable wind conditions (reference study)	500 MW wind farms installed and connected to Karlshamn through either the 130kV or the 400 kV busbar (both studies are made) Wind blowing with a mean speed of 8 m/s	The operation is stable; there are no observed stability problems, neither with respect to active or reactive power balance, and regardless of the voltage level at which the wind farm is connected. Some variations in the active power production from the wind turbine oscillate back and forth, but they are small, and not oscillating with frequencies that trig the power system oscillation modes.
	Response with wind blow up	As the reference study, but with an increase in wind speed of from 8 m/s to 18 m/s over 100 s	Connected to 130 kV: Active power balance is maintained throughout the blow up. The voltage profile for the neighbouring electric power systems is highly affected, due to reactive power imbalance caused by the increased reactive power consumption of the wind turbines. After approx. 50 s the south-eastern region suffer from under voltage problems on 130 kV level, and after approx. 90 s the Karlshamn 130 kV substation and its neighbouring substations suffer from voltage collapse. 400 kV remains in operation, though stressed from the voltage collapse. Connected on 400 kV: Active power balance is maintained throughout the blow up. The voltage profile for the neighbouring electric power systems is highly affected (but not as bad as in the 130kV study), due to reactive power imbalance caused by the increased reactive power consumption of the wind turbines. After approx. 80 s the Barsebäck region suffer from under voltage problems on both 400 kV and 130 kV level; voltage collapse does not occur.
	Response with wind blow down	As the reference study, but with a wind speed decrease from 8 m/s to 0 m/s over 100s	Connected to 130 kV: Active power balance is maintained throughout the blow down. When the blow down occurs, the voltage profile is stable, though with locally small voltage increases. After the wind speed has decreased both active and reactive power balance is maintained, and operations are steady. Connected on 400 kV: Active power balance is maintained throughout the blow down. When the blow down occurs, the voltage profile is stable, though with locally slight voltage increases (increases are smaller than when connected to 130 kV). After the wind speed has decreased both active and reactive power balance is maintained, and operations are steady.

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 50 % wind turbines and 50% CHP near Barsebäck	Response with stable wind conditions (reference study)	250 MW wind farms installed and 125 MW CHP and connected to Barsebäck through either the 130kV or the 400 kV busbar (both studies are made) Wind blowing with a mean speed of 8 m/s	The operation is stable; there are no observed stability problems, neither with respect to active or reactive power balance, and regardless of the voltage level at which the wind farm is connected. Some variations in the active power production from the wind turbine oscillate back and forth, but they are small, and not oscillating with frequencies that trig the power system oscillation modes.
	Response with wind blow up	As the reference study, but with an increase in wind speed of from 8 m/s to 18 m/s over 100 s	Connected to 130 kV: Active power balance is maintained throughout the blow up. The voltage profile for the neighbouring electric power systems is affected (though, significantly less than in the 100% wind case), due to reactive power imbalance caused by the increased reactive power consumption of the wind turbines. After approx. 90 s the Barsebäck region suffer from under voltage problems, especially on 130 kV level, and these under voltage problems persist, and the voltage level stabilises approx. 20% below rated voltage; voltage collapse does not occur. Connected on 400 kV: Active power balance is maintained throughout the blow up. The voltage profile for the neighbouring electric power systems is affected (but not as bad as in the 130kV study), due to reactive power imbalance caused by the increased reactive power consumption of the wind turbines. After approx. 130 s the Barsebäck region suffer from under voltage problems and voltage level persists on approx. 15% below rated voltage level ; but voltage collapse does not occur.
	Response with wind blow down	As the reference study, but with a wind speed decrease from 8 m/s to 0 m/s over 100s	Connected to 130 kV: Active power balance is maintained throughout the blow down. When the blow down occurs, the voltage profile is stable, though with locally small voltage increases. After the wind speed has decreased both active and reactive power balance is maintained, and operations are steady. Connected on 400 kV: Active power balance is maintained throughout the blow down. When the blow down occurs, the voltage profile is stable, though with locally slight voltage increases (increases are smaller than when connected to 130 kV). After the wind speed has decreased both active and reactive power balance is maintained, and operations are steady.

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 50 % wind turbines and 50% CHP near Gothemburg	Response with stable wind conditions (reference study)	250 MW wind farms installed and 125 MW CHP and connected to Gothemburg through the 400 kV busbar in the Gothemburg equivalent. Wind blowing with a mean speed of 8 m/s	The operation is stable; there are no observed stability problems, neither with respect to active or reactive power balance, and regardless of the voltage level at which the wind farm is connected. Some variations in the active power production from the wind turbine oscillate back and forth, but they are small, and not oscillating with frequencies that trig the power system oscillation modes.
	Response with wind blow up	As the reference study, but with an increase in wind speed of from 8 m/s to 18 m/s over 100 s	Active power balance is maintained throughout the blow up. The voltage profile for the neighbouring electric power systems is affected (but not as bad as in the 100% wind case), due to reactive power imbalance caused by the increased reactive power consumption of the wind turbines. After approx. 140 s the Gothemburg region suffers from local under voltage problems in Gothemburg with a voltage level of approx. 15% below rated voltage level., and the general voltage profile in all of the southern Swedish electric power system is affected, though voltage levels are not under 10-12% below rated voltage level. Voltage collapse does not occur.
	Response with wind blow down	As the reference study, but with a wind speed decrease from 8 m/s to 0 m/s over 100s	Active power balance is maintained throughout the blow down. When the blow down occurs, the voltage profile is stable, though with locally slight voltage increases. After the wind speed has decreased both active and reactive power balance is maintained, and operations are steady.

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 50 % wind turbines and 50% CHP near Karlshamn	Response with stable wind conditions (reference study)	250 MW wind farms installed and 125 MW CHP and connected to Karlshamn through either the 130kV or the 400 kV busbar (both studies are made) Wind blowing with a mean speed of 8 m/s	The operation is stable; there are no observed stability problems, neither with respect to active or reactive power balance, and regardless of the voltage level at which the wind farm is connected. Some variations in the active power production from the wind turbine oscillate back and forth, but they are small, and not oscillating with frequencies that trig the power system oscillation modes.
	Response with wind blow up	As the reference study, but with an increase in wind speed of from 8 m/s to 18 m/s over 100 s	Connected to 130 kV: Active power balance is maintained throughout the blow up. The voltage profile for the neighbouring electric power systems is affected, due to reactive power imbalance caused by the increased reactive power consumption of the wind turbines. After approx. 70 s the south-eastern region suffer from under voltage problems on 130 kV level and the Karlshamn 130 kV substation ends up having a voltage level on approx. 15% below rated voltage, where it stabilises. Voltages on 400 kV level are lowered, but not critically. Connected on 400 kV: Active power balance is maintained throughout the blow up. The voltage profile for the neighbouring electric power systems is highly affected (but not as bad as in the 130kV study), due to reactive power imbalance caused by the increased reactive power consumption of the wind turbines. After approx. 100 s the Karlshamn region suffer from under voltage problems on both 400 kV and 130 kV level, with voltages of approx 15-20% below rated voltage level; voltage collapse does not occur.
	Response with wind blow down	As the reference study, but with a wind speed decrease from 8 m/s to 0 m/s over 100s	Connected to 130 kV: Active power balance is maintained throughout the blow down. When the blow down occurs, the voltage profile is stable, though with locally small voltage increases. After the wind speed has decreased both active and reactive power balance is maintained, and operations are steady. Connected on 400 kV: Active power balance is maintained throughout the blow down. When the blow down occurs, the voltage profile is stable, though with locally slight voltage increases (increases are smaller than when connected to 130 kV). After the wind speed has decreased both active and reactive power balance is maintained, and operations are steady.

K.2. Tables showing results of simulations under faulty conditions

K.2.1. Simulations results in the Nordic 32 test system

Power system model	Simulation study	Short on the study	Observations
Simulations in Nordic 32 test system with 100 % wind turbines replacing Barsebäck	Response under line fall-out	As the reference study, but with the most loaded line over cut-set four fallen out	Operations are steady before line fall-out. The overall voltage profile in the southern Swedish electric power system immediately drops approx. 12-15% when the line falls out. Active power balance is maintained through-out the event. As concequence of the line fall out, the reactive power balance cannot be maintained in the southern Swedish electric power system, and as load restores after the line fall out, the over-all voltage profile worsens, and ultimately, voltage collapses after approx. 120 s.
	Response under unit tripping	As the reference study, but with the nearest unit tripping	As the observations under the line fall-out, but the over-all voltage drop is larger, approx. 15-20%. Voltage collapses after approx. 110 s.
	Response under 3 phase fault	As the reference study, but with a 100ms solid 3 phase fault in substation to which the wind farm is connected (short-circuit protection is not active)	Operations are steady before the fault. When the fault occurs, voltage immediately drops in the substations near the fault (usually such would result in disconnection of the faulted station, but in this case, protection is not active). When the fault is cleared, active and reactive power from the wind farm oscillates, resulting in oscillations in the frequency and the voltages in the whole system; voltage oscillations are worst in the southern Swedish electric power system, with oscillations of upto +/- 25-30%. After approx. 140 s. both active and reactive power balances is restored, and voltages and frequency is stable.

Power system model	Simulation study	Short on the study	Observations
Simulations in Nordic 32 test system with 50 % wind turbines and 50% CHP replacing Barsebäck	Response under line fall-out	As the reference study, but with the most loaded line over cut-set four fallen out	Operations are steady before line fall-out. The overall voltage profile in the southern Swedish electric power system immediately drops approx. 10% when the line falls out. Active power balance is maintained through-out the event. As concequence of the line fall out, the reactive power balance is stressed, but maintained. As the load restores after the line fall out, the over-all voltage level in the southern Swedish electric power system is lower, but stabilizes after a transient period of approx. 90 s.
	Response under unit tripping	As the reference study, but with the nearest unit tripping	As the observations under the line fall-out, but the over-all voltage drop is slightly larger, approx. 10-12% in the region.
	Response under 3 phase fault	As the reference study, but with a 100ms solid 3 phase fault in substation to which the wind farm is connected	Operations are steady before the fault. When the fault occurs, voltage immediately drops in the substations near the fault (usually such would result in disconnection of the faulted station, but in this case, protection is not active). When the fault is cleared, active and reactive power from the wind farm oscillates, resulting in oscillations in the frequency and the voltages in the whole system; voltage oscillations are worst in the southern Swedish electric power system, with oscillations of upto 20%. After approx. 90 s. both active and reactive power balances is restored, and voltages and frequency is stable.

K.2.2. Simulation results in the Sydkraft test system

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 100 % wind turbines near Barsebäck	Response under line fall-out	As the reference study, but with the most loaded line from the substations neighbouring Barsebäck fallen out (both studies of wind farm connection to 130 kV level and 400 kV level is studied)	Connected to 130 kV: Operations are steady before the line fall-out. After the line fall-out, the voltage levels in the Barsebäck substation drops severely, spreading to the neighbouring on both 130 kV and 400 kV level, until the Barsebäck 130 kV substation (to which the wind farm is connected) drops out after approx. 25 s. Hereafter, the voltage levels in the neighbouring substations oscillate and stabilizes on approx. the pre-fall-out voltage level. Connected to 400 kV: The development is practically the same as for the 130 kV study, but the time is for the substation disconnection is approx. 35 s.
	Response under unit tripping	As the reference study, but with the Sealand unit in Asnæs tripping	Connected to 130 kV: Operations are steady before the unit trips. After the unit tripping, the voltage levels in the Barsebäck substation drops initially approx. 25%, and accordingly in the whole south-western Swedish electric power system. Hereafter, the voltage levels in the neighbouring substations oscillate and is restored at approx. 15% below rated voltage level. Connected to 400 kV: The development is practically the same as for the 130 kV study, but the initial voltage drop is smaller, approx. 15% of rated voltage.
	Response under 3 phase fault	As the reference study, but with a 100ms solid 3 phase fault in substation to which the wind farm is connected	Connected to 130 kV: Operations are steady before the fault. When the fault occurs, voltage immediately drops in the substations near the fault (usually such would result in disconnection of the faulted station, but in this case, protection is not active). When the fault is cleared, active and reactive power from the wind farm oscillates, resulting in oscillations in the frequency and the voltages in the whole system; voltage oscillations are worst in the southern Swedish electric power system, with oscillations of upto 17-20%. After approx. 60 s. both active and reactive power balances is restored, and voltages and frequency is stable. Connected to 400 kV: Same as the 130 kV study, but the oscilltions are smaller, approx. 10-15% of rated voltage, and stability is restored faster, after approx. 45 s.

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 100 % wind turbines near Gothemburg	Response under line fall-out	As the reference study, but with the most loaded line over cut-set four fallen out	Operations are steady before the line fall-out. After the line fall-out, the voltage levels in southern Swedish electric power system in general drops on both 130 kV and 400 kV level, but after smaller oscillations it stabilizes on approx. 5-10% of the pre-fall-out voltage level.
	Response under unit tripping	As the reference study, but with the Ringhals unit equivalent tripping	Operations are steady before the unit trips. After the unit tripping, the voltage levels in the southern Swedish electric power system in general drops initially approx. 15-17%, and accordingly in the whole south-western Swedish electric power system. Hereafter, the voltage levels in the neighbouring substations oscillate and is restored at approx. 10-15% below rated voltage level.
	Response under 3 phase fault	As the reference study, but with a 100ms solid 3 phase fault in Gothemburg equivalent substation to which the wind farm is connected	Operations are steady before the fault. When the fault occurs, voltage immediately drops in the substations near the fault. When the fault is cleared, active and reactive power in the whole electric power system. Voltage oscillations are worst in the mid and southern Swedish electric power system, with oscillations of upto 10-15%. After approx. 50 s. both active and reactive power balances is restored, and voltages and frequency is stable.

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 100 % wind turbines near Karlshamn	Response under line fall-out	As the reference study, but with the most loaded line from the neighbouring substations fallen out	Connected to 130 kV: Operations are steady before the line fall-out. After the line fall-out, the voltage levels in the Karlshamn substation and the neighbouring substationsdrops severely both 130 kV and 400 kV level, until the Karlshamn 130 kV substation falls out. Hereafter, the voltage levels in the neighbouring substations oscillate and stabilizes on approx. the pre-fall-out voltage level. Connected to 400 kV: The development is practically the same as for the 130 kV study.
	Response under unit tripping	As the reference study, but with the Karlshamn unit tripping	Connected to 130 kV: Operations are steady before the unit trips. After the unit tripping, the voltage levels in the Karlshamn substation drops initially approx. 20%, and accordingly in the whole south-eastern Swedish electric power system. Hereafter, the voltage levels in the neighbouring substations oscillate and is restored at approx. 10-12% below rated voltage level. Connected to 400 kV: The development is practically the same as for the 130 kV study, but the initial voltage drop is smaller, approx. 10% of rated voltage.
	Response under 3 phase fault	As the reference study, but with a 100ms solid 3 phase fault in substation to which the wind farm is connected	Connected to 130 kV: Operations are steady before the fault. When the fault occurs, voltage immediately drops in the substations near the fault. When the fault is cleared, active and reactive power from the wind farm oscillates, resulting in oscillations in the frequency and the voltages in the whole system; voltage oscillations are worst in the southern Swedish electric power system, with oscillations of upto 17-20%. After approx. 50 s. both active and reactive power balances is restored, and voltages and frequency is stable. Connected to 400 kV: Same as the 130 kV study, but the osciall-tions are smaller, approx. 10-15% of rated voltage, and stability is restored faster, after approx. 40 s.

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 50 % wind turbines and 50% CHP near Barsebäck	Response under line fall-out	As the reference study, but with the most loaded line from the substations neighbouring Barsebäck fallen out (both studies of wind farm connection to 130 kV level and 400 kV level is studied)	Connected to 130 kV: Operations are steady before the line fall-out. After the line fall-out, the voltage levels in the Barsebäck substation and the neighbouring substations drops on both 130 kV and 400 kV level. Hereafter, the voltage levels in the neighbouring substations oscillate and stabilizes on approx. the pre-fall-out voltage level, and no disconnection of substations nor any voltage collapses occur. . Connected to 400 kV: The development is practically the same as for the 130 kV study.
	Response under unit tripping	As the reference study, but with the Sealand unit in Asnæs tripping	The development for both the studies, with the embedded generation connected to respectively 130 kV and 400 kV, is practically the same as for the 100% wind turbine study. Oscillation levels and times are in the same range.
	Response under 3 phase fault	As the reference study, but with a 100ms solid 3 phase fault in substation to which the wind farm is connected	Connected to 130 kV: Similar to the 100% wind turbines study. Though, oscillations in the frequency and the voltages are smaller than in the 100% wind turbine case,(voltage oscillations are upto 10-15%) and the restoration time for the active and reactive power balances is smaller (approx. 50 s). Connected to 400 kV: Same as the 130 kV study, but with even smaller oscialltions in frequency and voltage levels.

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 50 % wind turbines and 50% CHP near Gothemburg	Response under line fall-out	As the reference study, but with the most loaded line over cut-set four fallen out	The observed consequences are similar to the ones observed in the 100% wind turbine study, but the voltage level profile is less affected.
	Response under unit tripping	As the reference study, but with the Ringhals unit equivalent tripping	Similar to the 100% wind turbine case, with slightly smaller oscillations in voltage level, and with power balance restoration within the same time ranges
	Response under 3 phase fault	As the reference study, but with a 100ms solid 3 phase fault in Gothemburg equivalent substation to which the wind farm is connected	The observed consequences are similar to the ones observed in the 100% wind turbine study, though with smaller oscillations in voltage levels and with faster stability restoration.

Power system model	Simulation study	Short on the study	Observations
Simulations in Sydkraft test system with 50 % wind turbines and 50% CHP near Karlshamn	Response under line fall-out	As the reference study, but with the most loaded line over cut-set four fallen out	Connected to 130 kV: Similar to the 100% wind turbine study, but the consequences to the voltage level profile is smaller Connected to 400 kV: Similar to the 100% wind turbine study, but the consequences to the voltage level profile is smaller
	Response under unit tripping	As the reference study, but with the nearest unit tripping	The development for both the studies, with the embedded generation connected to respectively 130 kV and 400 kV, is practically the same as for the 100% wind turbine study. Oscillation levels and times are in the same range.
	Response under 3 phase fault	As the reference study, but with a 100ms solid 3 phase fault in substation to which the wind farm is connected	Connected to 130 kV: Similar to the 100% wind turbines study. Though, oscillations in the frequency and the voltages are smaller than in the 100% wind turbine case, and the restoration time for the active and reactive power balances is smaller. Connected to 400 kV: Same as the 130 kV study, but with even smaller oscillations in frequency and voltage levels.

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