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Power Quality Disturbances in Production Facilities

Bachelor of Science Thesis

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2012

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Cover:
Wind farm consisting of large three-bladed horizontal axis wind turbines. Reproduced with permission from WSP Sverige AB.

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Abstract

This thesis is performed for WSP as a part of a longer process to increase WSP's knowledge of power quality disturbance mitigation in production facilities; mainly wind farms. The different types of power quality disturbances are defined and their causes and effects explained. A wide range of available devices which can be used to mitigate these disturbances are reviewed. The basics of wind power are also explained briefly, including a review of different turbine types. The broad range variable-speed turbine types – where the turbine is controlled through a frequency converter – are today very dominant. The central part of the thesis describes how disturbances are handled in wind farms. Mainly, flicker and harmonics have to be considered, but also unbalance, rapid voltage changes, voltage dips, transient overvoltages and frequency variations. Flicker severity is subjective and therefore flicker is difficult to quantify. However, flicker seldom requires special mitigation in new wind farms. Harmonics are the main problem and are eliminated with passive filters, primarily placed inside of the turbines, at the converters. Also, amplification of existing harmonics due to resonance effects needs to be considered. General allowed levels in the power system for each disturbance type are presented. Allowed emission levels for a specific wind farm are set by the network owner after calculations of the power system impedance have been performed. A computer-based tool for choosing mitigation devices was originally planned to be designed in this thesis, but this idea was abandoned when it became clear that only filters are used in practice and that their properties are proprietary information. Lastly, some possible future developments of wind power and the power system which could affect disturbance mitigation are discussed.

Keywords: Power quality, disturbances, mitigation, flicker, harmonics, filters, wind farms

Preface

This thesis was made possible by WSP Systems in Göteborg. I would like to thank everyone there for the warm welcome and support and for giving me a place to work in. A special thanks to Gordon Johansson and Fredrik Lundmark for being supervisors for this thesis project and always being available for answering questions.

At Chalmers I would like to thank my examiner and supervisor Massimo Bongiorno for invaluable guidance in writing this report and also for making sure I learned as much as possible from this thesis project.

I would also like to thank the following people for providing me with interviews: Christer Liljegren (Cleps AB), Anders Petersson (Svenska Kraftnät), Gunilla Brännman (Vattenfall), and Jon Jensen (Siemens). Your willingness to help was very much appreciated. Thank you for giving me insight into how the power system works and how disturbance mitigation is handled in practice.

Emanuel Widlund

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Table of Contents

Abbreviations

AC – Alternating Current

BSES – Backup Stored Energy System

$\mathbf{c(\psi_k,\nu_a)}$ – flicker coefficient

$\mathbf{c_p}$ – power coefficient

CPU – Central Processing Unit

CSC – Current Source Converter

CVT – Constant Voltage Transformer

DC – Direct Current

DFIG – Double-Fed Induction Generator

DFT – Discrete Fourier Transform

DVR – Dynamic Voltage Restorer

$\mathbf{f_0}$ – resonant frequency

FACTS – Flexible AC Transmission System

GTO – Gate Turn-Off thyristor

HV – High Voltage

IEC – International Electrotechnical Commission

IEEE – Institute of Electrical and Electronics Engineers

IGBT – Insulated Gate Bipolar Transistor

$\mathbf{k_f(\psi_k)}$ – flicker step factor

$\mathbf{k_u(\psi_k)}$ – voltage change factor

LIPC – Low Impedance Power Conditioner

LV – Low Voltage

M-G Set – Motor-Generator Set

MOSFET – Metal Oxide Semiconductor Field-Effect Transistor

MOV – Metal Oxide Varistor

MV – Medium Voltage

N_{10m} – maximum possible switching events per 10 min period

N_{120m} – maximum possible switching events per 120 min period

$P_{0.1}$ – the flicker level exceeded 0.1 percent of the time

P_{1s} – the flicker level exceeded 1 percent of the time

P_{3s} – the flicker level exceeded 3 percent of the time

P_{10s} – the flicker level exceeded 10 percent of the time

P_{50s} – the flicker level exceeded 50 percent of the time

PCC – Point of Common Coupling

PEV – Plug-in Electric Vehicle

PL – Planning Level (sv: Planeringsnivå)

P_{LT} – Long-Term value for flicker severity

$P_{LT\,\Sigma}$ – Long-Term value for flicker severity for an entire wind farm

P_{ST} – Short-Term value for flicker severity

$P_{ST,fic}$ – Short-Term value for flicker severity of a fictitious grid

$P_{ST\,\Sigma}$ – Short-Term value for flicker severity for an entire wind farm

PWM – Pulse Width Modulation

R_k – grid resistance

RMS – Root Mean Square

SEK – Svenska Elektriska Kommittén (en: Swedish Electrical Committee)

SiC – Silicon Carbide

S_k – apparent short-circuit power of an actual grid

$S_{k,fic}$ – apparent short-circuit power of a fictitious grid

SLG – Single Line-to-Ground

SMC – Soft Magnetic Composite

SMES – Superconducting Magnetic Energy Storage

S_n – rated apparent power of a wind turbine

SRM – Switched Reluctance Machine

SRS – Stockholm Royal Seaport (sv: Norra Djurgårdsstaden)

SSC – Static Series Compensator

STATCOM – STATic synchronous COMpensator

STS – Static Transfer Switch

SVC – Static VAr Compensator

SvK – Svenska Kraftnät (en: Swedish National Grid)

SVR – Static Voltage Regulator

TCR – Thyristor Controllable Reactor

TFM – Transverse Flux Machine

THC – Total Harmonic Current distortion

THD – Total Harmonic Distortion

TL – Target Limit (sv: Målgräns)

TSC – Thyristor Switched Capacitor

TVSS – Transient Voltage Surge Suppressor

UHV – Ultra-High Voltage

$\mathbf{U_1}$ – RMS voltage of the fundamental frequency component

$\mathbf{U_h}$ – RMS voltage of the h^{th} integer harmonic component

$\mathbf{u_h}$ – relative voltage magnitude of the h^{th} integer harmonic component

$\mathbf{U_n}$ – nominal voltage

UPQC – Unified Power Quality Conditioner

UPS – Uninterruptable Power Supply

VPP – Virtual Power Plant

VSC – Voltage Source Converter

VSI – Very Short Interruption

$\mathbf{X_C}$ – reactance of capacitor

$\mathbf{X_k}$ – grid reactance

X_L – reactance of inductor

ZnO – Zinc Oxide

ΔU_{max} – maximum relative change in RMS voltage during a rapid voltage change

ΔU_{stat} - relative change in RMS voltage before and after a rapid voltage change

ρ – air density

v_a – wind velocity

ψ_k – grid angle

1. Introduction

1.1. Background

This thesis deals with how the power quality disturbances can be mitigated in large production facilities, with a strong focus on large wind farms. The work is done on behalf of WSP Systems' Electric Power Department in Göteborg. Supervisor for the project from WSP has been Gordon Johansson and Fredrik Lundmark and the examiner and supervisor from Chalmers has been Massimo Bongiorno. This thesis is part of a process that preliminarily will consist of a total of three diploma theses performed on behalf of WSP Systems, which together will result in a way of ascertaining the best mitigation methods for power quality disturbances during the project phase of new production facilities (mainly wind farms) on the basis of agreed parameters. This thesis will provide the theoretical basis for the later modeling and calculations.

1.2. Aim

Firstly, this thesis aims to explain what types of power quality disturbances exist, their causes and negative impact on the power system. Secondly, this thesis reviews the methods that are available for handling the power quality disturbances studied in part one. Thirdly, a brief introduction to wind power is given. Then, a detailed analysis of the disturbance types and mitigation methods relevant for wind farms is performed. Furthermore, the possibility of designing a computer-based tool to assist in the choice of mitigation method for power quality disturbances during the design of WSP's future production facilities (wind farms) is investigated. Lastly, an examination is made into if there is a different approach to power quality disturbances mitigation than the one currently used in Sweden, and if so if using this other approach could increase efficiency and enhance the stability of the Swedish electric power system. This part also examines how disturbance mitigation could change in the future due to developments in wind power or power system technology.

The academic contribution of this thesis project consists of making a connection between academic theories about power quality disturbance mitigation, the rules and regulations of the Swedish Standard (sv: Svensk Standard) and the way the disturbance mitigation theories are actually being applied in the Swedish power system when new wind farms are built.

1.3. Limits

The examination of both the disturbance types and their mitigation methods is concentrated around what is common and applicable for land-based wind power production facilities. Remaining disturbance types and mitigation methods are only described briefly. Also, only methods which are actually used to a large extent in the Swedish power system or methods which could replace the former methods without extensive reconstruction of the power system, severely increased costs or an unacceptable drop in power quality are examined in detail. The details about mitigation methods internally in the turbines are limited due to confidentiality policies of wind turbine manufacturers resulting in the thesis focusing more on disturbances as seen from the grid. Furthermore, the last of the four aims of the thesis is of a lower priority and was only pursued after the successful conclusion of the three prioritized aims, and then only to the extent the remaining time permitted.

1.4.Problem Description

What are the different types of power quality disturbances and how do they affect the power system?

Which of these disturbances are caused by production facilities (wind farms) in the Swedish power system?

Which of the disturbances caused by wind farms are the most frequent and cause the most problems in the electrical power system, i.e. are the most important to mitigate?

What methods are available for power quality disturbance mitigation?

Which of these methods are used in the Swedish power system today?

Which methods are the most used/suitable for mitigating power quality disturbances generated by newly constructed wind farms?

For the latter methods, do parameters such as the number of wind turbines and their size affect the choice of mitigation method for new wind farms?

How can an easy-to-use computer-based tool be designed to, by insertion of such parameters, generate recommendations for appropriate disturbance mitigation methods for a specific facility being designed and is such a tool useful?

Could a different approach to power quality disturbance mitigation than the current one increase the efficiency and enhance the stability of the Swedish power system?

How is the mitigation of power quality disturbances likely to change in the future with respect to factors such as the development of new mitigation methods, a new division of the power generation between the various energy sources (e. g. due to a large increase in the installed amount of wind power) or a restructuring of the electric power system to meet new needs, such as increased use of electric vehicles and/or increased small-scale energy production (Smart Grid)?

1.5.Method

The academic literature was gathered mainly through the resources of Chalmers' library. A large number of both physical and electronic books were collected, written by both foreign and Swedish scholars. Some literature was generally about power quality and some was focused on wind power applications. These publications were cross-referenced to reveal which information was universally agreed on and should therefore be included in the report. The bulk of the literature was no older than five years, and almost none over fifteen years old – this to avoid obsolete theories and methods being described in this thesis. These academic publications provided the foundation of the thesis, especially for the overviews of disturbance types, mitigation methods and wind power.

To ensure relevance to the Swedish power system appropriate parts of the Swedish Standard were acquired through sources at both WSP and Chalmers and the academic literature was compared to these to avoid including facts in the thesis only pertinent to power systems of other types than the Swedish system. Also, it was important to ensure the correct definitions of phenomena and power system parameters were used.

Interviews were conducted with representatives from companies active in the wind farm construction sector, to acquire knowledge of how the academic theories are applied today in the Swedish power system. Representatives from network owners (Svenska Kraftnät and Vattenfall) and a turbine constructor (Siemens) as well as an independent consultancy firm (Cleps AB) were interviewed. Important information from these sources included which power quality disturbances are considered when constructing wind farms, what parameters are considered when choosing mitigation methods for those disturbances as well as what the priorities of the companies are in selecting and approving mitigation techniques, with respect to e. g. economics, complexity, size, life span etc. Also, general knowledge was gained about the responsibility structure of the Swedish power system, including how and by whom rules and limits for power quality are decided.

For reasons described in Chapter 7 of this report the investigation of whether to create a computer-based tool as a part of this thesis concluded that such a tool was neither practically possible nor needed. The idea proved too far removed from the practical reality of power quality disturbance mitigation for such a tool to be useful.

2. Power Quality, A Brief Introduction

Power quality is a wide subject without a universally agreed definition. The definition of power quality used in this report is as follows: "Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy". The highest power quality is achieved when voltage and current have purely sinusoidal waveforms containing only the power frequency (50 Hz in Sweden) and when the voltage magnitude corresponds to its reference value. Any deviation from this may negatively affect the function and/or life expectancy of equipment connected to the power system. [1]

This report will deal with the variety of phenomena which can distort the current and voltage waveforms, so called power quality disturbances, and how to prevent these phenomena from occurring or counteract their negative influence on the power quality. The goal is to arrive at voltage and current waveforms within the allowed limits according to the Swedish standards and regulations providing the electrical boundaries mentioned above in the definition of power quality. The Swedish rules are derived from the rules set by the IEC (International Electrotechnical Commission) of which SEK (Svenska Elektriska Kommittén; en: Swedish Electrical Committee), who sets the Swedish rules, is the Swedish national committee. [2]

3. Power Quality Disturbance Types

There are a number of different types of power quality disturbances and also a number of different ways to define and categorize them. Here follows one possible list of power quality disturbances types, categorized in one of many possible ways. Definitions of the different disturbance types in accordance with the Swedish Standard as well as usual causes and common negative effects of them are included; and also some illustrative figures of the phenomena where this might be helpful.

3.1. Long-Duration Voltage Variations

This category includes disturbances with a large spectrum of possible durations, including very long durations, and with less clear definitions than those in the coming categories. Generally interruptions, undervoltages, overvoltages, and rapid voltage changes can be considered steady-state disturbances, in contrast to for example voltage dips and swells and transients (see Chapters 3.2 and 3.5 respectively), which are similar phenomena but transitory in nature. [3]

3.1.1. Interruptions

An interruption is an event defined in the Swedish Standard as a state during which the RMS value of the voltage at the supply terminal is below 5 % of its reference value. For three-phase systems the voltage must be below this limit in all three phases to constitute an interruption, otherwise the event is classified as a voltage dip (see Chapter 3.2.1), or an undervoltage if it persists long enough (see Chapter 3.1.2). According to the IEEE (Institute of Electrical and Electronics Engineers; non-profit association for advancement of technology based in the USA) Standard, however, the border between interruption and voltage dip is at 10 % of the reference voltage. Caution is therefore advised when discussing these phenomena; be sure to establish which definitions should be used. In this thesis the definitions according to the Swedish Standard will be used. [2,4]

Interruptions are classified as planned interruptions if the network users were informed about them in advance, otherwise as temporary interruptions. With respect to duration a temporary interruption is classified as a long interruption if its duration exceeds 3 min and otherwise as a short interruption (see Figure 1) according to the Swedish Standard. The term “very short interruption” (VSI) can be used to describe an interruption shorter in duration than 1 s to 5 s and also the term “outage” can be used to describe an interruption shorter than 1 min. [2]

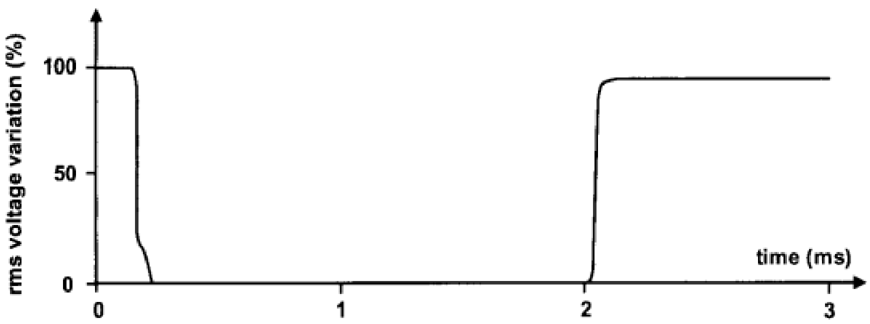

Figure 1. Short interruption due to a fault. [5]

Planned interruptions are usually caused by construction or maintenance in the power system. Temporary interruptions are usually caused by faults and are generally unpredictable and random occurrences. VSIs are usually caused by self-clearing faults in a system capable of automatic re-connection. [2]

3.1.2. Overvoltages & Undervoltages

An overvoltage can be defined as any voltage between one phase conductor and ground or between phase conductors having a peak value exceeding the corresponding peak of the highest voltage allowed for adjacent equipment. An analog definition can be applied for undervoltages. With these broad definitions over and undervoltages can be said to contain most other voltage disturbances mentioned below. However, in this report over and undervoltages will be the terms used to describe deviating voltages which cannot be classified under any of the more clearly defined disturbance types mentioned below. For example most long-duration voltage variations will be defined as under- or overvoltages. [6]

Common causes of undervoltages include faults, reduction in supply capability, and overload. Overvoltages can be caused by lightning, switching events, insulation faults, and faults with alternator regulators or tap changer transformers, as well as over compensation etc. [4]

The effects of undervoltages are usually increasing currents drawn by motors, increased reactive power demand, and voltage instability. For overvoltages common effects also include increased reactive power demand and voltage instability, as well as heightened stress on insulation. [4]

3.1.3. Rapid Voltage Changes

A special subtype of long-duration voltage variations is rapid voltage changes, or voltage steps. These are defined in the Swedish Standard as solitary rapid changes in the RMS value of the voltage between two consecutive levels with limited but not specified duration. The change must be more rapid than 0.5 % per second and keep within 90 - 110 % of the reference value – a larger magnitude leads to reclassification as a voltage dip or swell (see Chapter 3.2). [2,7]

These changes are usually caused by load changes, switching events in the power system and faults. The effects of rapid voltage changes are similar to those of flicker (see Chapter 3.3.1). Above a certain level rapid voltage changes cause visible light intensity changes in incandescent light sources (e. g. common light bulbs). These changes can cause discomfort to people exposed. Effects of rapid voltage changes are commonly mistaken for effects of flicker, because of the similarities between the two. [2,8]

3.2. Voltage Dips (Sags) & Voltage Swells

These types of disturbances have durations of between 10 ms (0.5 cycles) and 1 min according to the Swedish Standard. This duration is measured from the crossing of the start threshold to the crossing of the end threshold. For three-phase systems the duration is measured from when one phase has crossed the start threshold to when all three phases have crossed the end threshold. Voltage dips are much more common than voltage swells. [2,4]

3.2.1. Voltage Dips (Sags)

According to the Swedish Standard the start threshold is equal to 90 % of the reference voltage for voltage dips (called voltage sags in America). The end threshold is usually set 1 - 2 % of the reference voltage above the start threshold. Consequently, the duration of a voltage dip is measured from when the first phase drops below 90 % of the reference voltage until all three phases have again risen above 91 % - 92 % of the reference voltage. As previously mentioned, if all phases drop below 5 % of the reference voltage or the duration exceeds 1 min the event will be re-classified as an interruption or an undervoltage respectively. [2,6]

Main causes of voltage dips include energizing of heavy loads (e. g. arc furnaces), starting of large induction motors, single line-to-ground (SLG) faults (see Figure 2), line-line and symmetrical faults, and transference of load from one power source to another. [4]

Effects of voltage dips mainly include voltage instability and malfunctions in electrical low-voltage devices, uninterruptible power supplies, and measuring and control equipment. Also, problems in interfacing with communication signals can arise. [4]

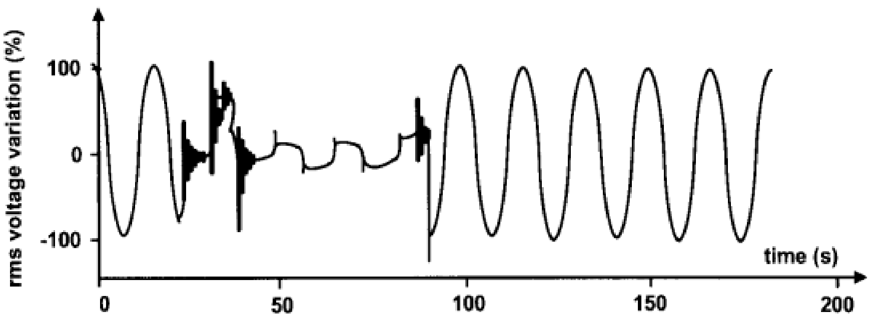

Figure 2. Voltage dip caused by an SLG fault. [5]

3.2.2. Voltage Swells

For voltage swells the start threshold is equal to 110 % of the reference voltage according to the Swedish Standard. The end threshold is usually set 1 - 2 % of the reference voltage below the start threshold. In other words, the duration of a voltage swell is measured from when one phase rises above 110 % of the reference voltage until all three phases have again fallen below 108 % - 109 % of the reference voltage. If the event persists longer than 1 min it will be re-classified as an overvoltage. [2,6]

Main causes of voltage swells include energizing of capacitor banks, shutdown of large loads, unbalanced faults (one or more phase-to-phase voltages will increase, see Figure 3), transients (see Chapter 3.5), and power frequency surges (see Chapter 3.9). [4]

The effects of voltage swells are largely the same as for voltage dips (see Chapter 3.2.1). [6]

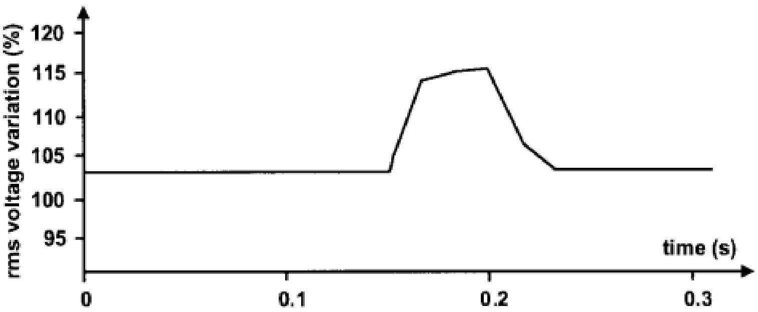

Figure 3. Voltage swell in the phase-to-phase voltage between a faultless phase and the faulted phase during an SLG fault. [5]

3.3. Voltage Fluctuations

Voltage fluctuations are defined in the Swedish Standard as a series of voltage changes or a cyclic variation of the envelope of the voltage. These voltage changes are commonly between 90 - 110 % of the reference voltage and are considered steady-state disturbances. [2,3,4]

Main causes of voltage fluctuations are startup of drives and drives with rapidly changing load or load impedance, as well as operation of arc furnaces (see Figure 4), pulsed-power outputs, resistance welders, and rolling mills. [4]

Common effects of voltage fluctuations are decreased performance and instability of the internal voltages and currents of electronic equipment, as well as problems with reactive power compensation. [4]

3.3.1. Flicker

Voltage fluctuations can cause the visual phenomenon known as flicker. This consists of changes in intensity or spectral components of light sources as a result of continuous rapid changes in load current. This phenomenon can, when it reaches certain amplitudes (different amplitudes depending on the frequency of the flicker), cause discomfort for people exposed to the effects. However, flicker does not cause any malfunctions in the power system; the inducted discomfort is its only negative effect. Flicker is sometimes considered a subtype of voltage fluctuations, not an effect of the same. [3,4]

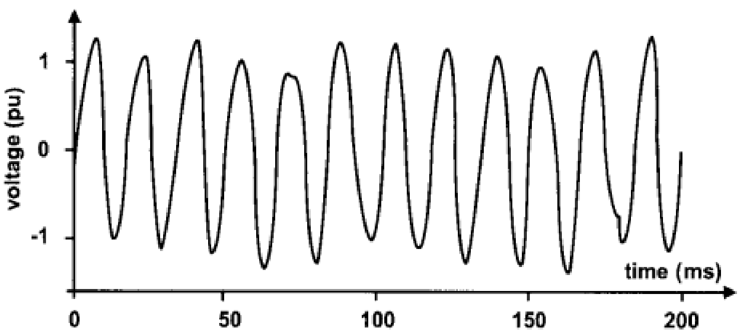

Figure 4. Voltage fluctuations caused by arc furnace operation. [5]

3.4. Voltage/Current Unbalance

Voltage unbalance according to the Swedish Standard is a condition in a multiple-phase system during which the RMS values of the phase voltages or the phase angles between adjacent phases are not equal. An analog definition can be made for current unbalance. In a three-phase system voltage unbalance occurs when the magnitude of the three phase voltages are not exactly equal or the phase angle between phases is not exactly 120^o. Unbalance disturbances can be divided into steady-state unbalances and transient unbalances depending on the duration and cause of the unbalance. [2,4]

Common causes of steady-state unbalance include non-transposed overhead transmission lines and unbalanced single-phase loading of three-phase systems. For transient unbalance common causes are blown out fuses in one of the phases in a capacitor bank and single or double line-to-ground faults. [4]

During unbalance negative sequence components (see Chapter 3.6.2.1) appear, resulting in different currents being drawn in different phases. This causes torque ripple in three-phase motors, as well as hampers their performance and causes unequal losses and heating between the phases and their loads. The torque ripple can lead to excessive wearing and thereby shortened life span of the motors. Furthermore, reactive power demand will increase and reactive power compensation will become more difficult. The end result can be mal-operation of equipment and measuring instruments, as well as shortened life spans of appliances. [4]

3.5. Transients

Transients, or transient overvoltages, are short-duration either oscillating or impulsive voltage phenomena with a duration of usually a few milliseconds or shorter and normally heavily dampened. Though short in duration they often create very high magnitudes of voltage. [2,4]

Transients with high voltage magnitudes cause insulation breakdown in the power system and transients with high current magnitudes can burn out devices and instruments. Other effects of transients include mal-operation of relays and mal-tripping of circuit breakers. [4]

3.5.1. Impulsive transients

Impulsive transients (sometimes referred to as surges) are unidirectional, i. e. never switch polarity. They are often described with rise time (time to reach the voltage peak), time-to-half (time until the surge has decayed to half the peak value) and peak voltage magnitude. Their duration is usually very short, often below one millisecond and their spectral components are often very high frequent. [9]

The main cause of impulsive transients is lightning strikes (see Figure 5). [9]

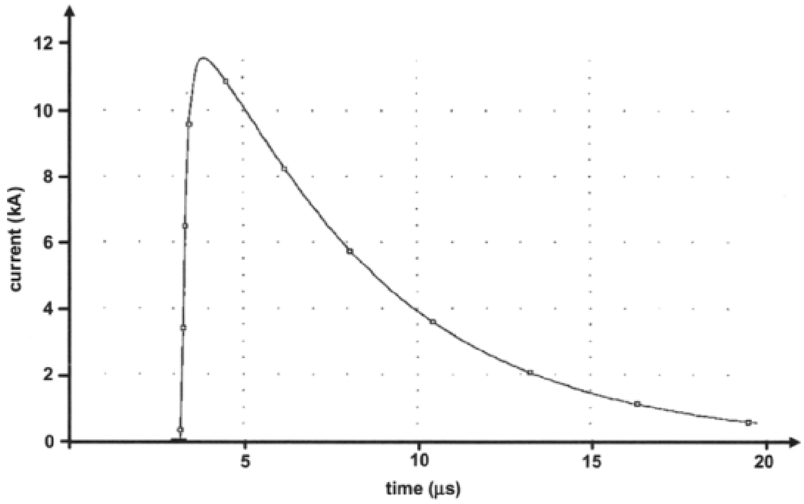

Figure 5. Impulsive transient current caused by a lightning strike, result of PSpice simulation. [5]

3.5.2. Oscillatory transients

Oscillatory transients rapidly switch polarity, often numerous times during their existence. Their duration is often longer than for the impulsive transients, whereas their spectral components can be of a wide range of frequencies, from a few hundred Hertz up to hundreds of kilohertz. Oscillatory transients can be divided into subgroups based on their predominant frequency (high-, medium-, and low-frequent). [9]

Among the many usual causes of oscillatory transients are energizing of transformers, capacitors (see Figure 6), lines, and cables, as well as re-strike during capacitor de-energizing, cable switching, ferroresonance, and system response to impulsive transients. [4,6]

Repeated oscillatory transients can cause the magnetic properties of core materials used in electrical machines to change. [4]

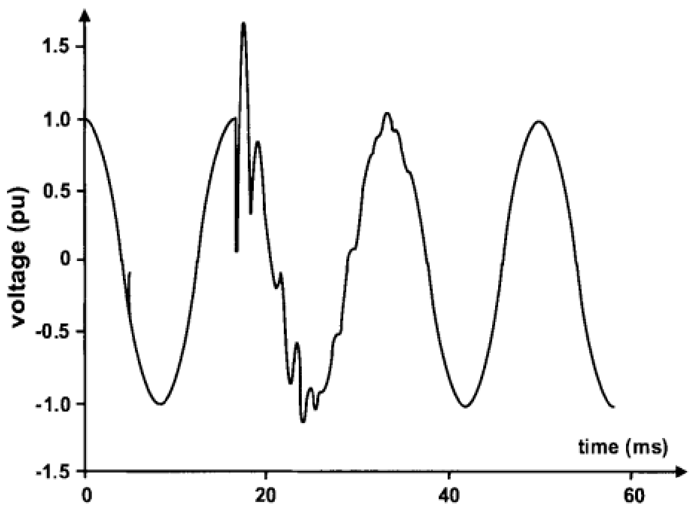

Figure 6. Low-frequent oscillatory transient caused by capacitor bank energizing. [5]

3.6. Waveform distortion

Waveform distortion is defined as a steady-state deviation from an ideal sine wave of power frequency, primarily categorized by the spectral content of the deviation. There are four major subtypes: DC offset, harmonics, notching, and electric noise. Harmonics are further divided into integer harmonics, interharmonics, and subharmonics. [9]

3.6.1. DC Offset

A DC offset is a DC component of the voltage or current in an AC system. Main causes are rectifiers or other electronic switching devices being operated in the power system, as well as transformer saturation and geomagnetic disturbances. Faults in electrical machines can also cause severe transient DC offsets. [4]

Possible negative effects of a DC offset in an AC network are half-cycle saturation of transformer cores, generation of even integer harmonics (see Chapter 3.6.2.1), and increased temperatures in transformers, rotating machines, and electromagnetic devices which may shorten their lifetime, as well as electrolytic erosion of grounding electrodes and other connectors. [4]

3.6.2. Harmonics

Harmonics are sinusoidal components of the system voltage or current with frequencies other than the power frequency, also called the fundamental frequency. [4]

Harmonics in general are often caused by operation of rotating machines, arcing devices, semiconductor based power supply systems, converter-fed AC drives, thyristor controlled reactors, phase controllers, and AC regulators, as well as magnetization nonlinearities of transformers. [4]

The general effects of harmonics include increased thermal stress and losses in capacitors and transformers, as well as poor damping, increased losses, and in other ways degraded performance of rotating motors. Furthermore, transmission systems are subject to higher copper losses, corona, skin effect, and dielectric stress and also interference with measuring equipment and protection systems. [4]

Harmonics also negatively affect consumer equipment such as television receivers, fluorescent and mercury arc lighting, and the CPUs and monitors of computers. [4]

The three subtypes of harmonics – integer harmonics, interharmonics and subharmonics – are briefly described below.

3.6.2.1. Integer Harmonics

Integer harmonics (sometimes just called harmonics, however not in this thesis) have frequencies which are integer multiples of the fundamental frequency. Integer harmonics can be divided into odd and even integer harmonics depending on whether their frequencies are odd or even integer multiples of the fundamental frequency, with the odd harmonics being overwhelmingly more common in the power system. [4,9]

A further division of the odd integer harmonics into three harmonic phase sequences is very useful. The method of phase sequence components allows transformation of any unbalanced set of three-phase voltages or currents into three balanced sets: A positive-sequence set with the same phase sequence as the normal three-phase system (A-B-C), a negative-sequence set with opposite phase rotation (A-C-B), and a zero-sequence set with no phase rotation (same phase angle for all three phases). [9]

An important subtype of odd integer harmonics, consisting of zero-sequence harmonics, is triplen harmonics. These are odd multiples of the third harmonic, i. e. have frequencies of 3, 9, 15 etc. times the fundamental frequency. Since triplen harmonics are predominantly zero-sequence harmonics the triplen harmonic contributions from all three phases will be added in neutral conductors, where such exist, and therefore triplen harmonics might have to be given special consideration in some cases. [9]

Integer harmonics are caused by nonlinear loads and other nonlinear equipment in the power system. [9]

3.6.2.2. Interharmonics

Interharmonics have frequencies higher than the fundamental, but not integer multiples of it. Main sources of integer harmonics include frequency converters, cycloconverters, induction furnaces, and arcing devices. Interharmonics are often load dependent, i. e. are not constant over time, and products of frequency conversion. [4,9]

Interharmonics have been known to cause flicker (see Chapter 3.3.1) and slow oscillating power frequency variations (see Chapter 3.7). [8]

3.6.2.3. Subharmonics

Subharmonics have lower frequencies than the fundamental frequency. These are rare harmonic disturbances. [4]

3.6.3. Notching

Notching disturbances are non-sinusoidal, periodic waveform distortions and, as the name suggests, consist of notches in the fundamental sine wave component. This is caused by the commutation of current from one phase to another during the continuous operation of power electronic devices (see Figure 7). [9]

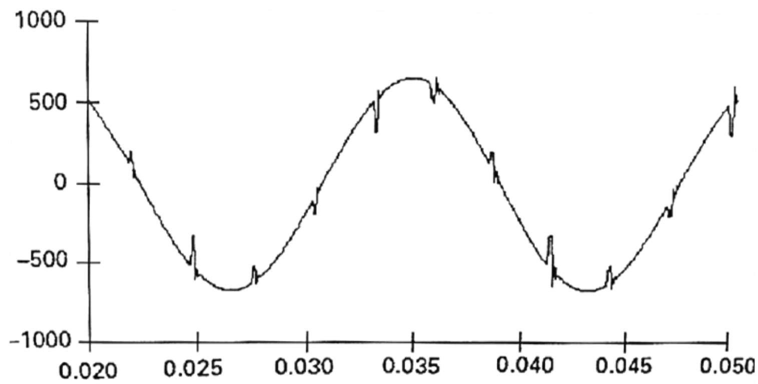

Figure 7. Voltage notching caused by a three-phase converter. [9]

Excessive levels of notching can lead to problems in the operation of sensitive communication or data-processing loads. [1]

3.6.4. Electric Noise

Electric noise (or electrical noise) is made up of low magnitude electrical signals from a broad frequency spectrum lower than 200 kHz. Noise is commonly used to describe all sorts of unwanted waveform distorting signals which cannot be classified as harmonics, notching or DC Offset, or sometimes as an even broader term. [9]

There are numerous possible sources including faulty connections in transmission or distribution systems, arc furnaces, electrical furnaces, power electronic devices, control circuits, welding equipment, loads with solid-state rectifiers, improper grounding, and turning off capacitor banks, as well as adjustable-speed drives, corona, and interference with communication circuits. [4]

Electric noise can have negative effects on the operation of electronic devices like microcomputers and programmable controllers. [4]

3.7. Power Frequency Variations

As the name suggests, power frequency variations are deviations from the desired power frequency, in Sweden 50 Hz. The main cause is a discrepancy between active power consumption and generation, which causes changes in the rotational speed of electromechanical generators. Faults can also cause frequency variations. [5]

4. Mitigation Methods for Power Quality Disturbances

Here follows a general review of what theoretical mitigation methods are available for the different types of power quality disturbances. This review does not claim to be all-encompassing, but the aim is to include the most common and some promising new mitigation methods and to list at least one mitigation method for each of the disturbance types reviewed in Chapter 3, even though some disturbance types are very much more common than others.

The focus of this review lies on mitigation devices rather than mitigation through the design of the power system and the production facilities and loads connected to it. This review is too general and brief for it to encompass design issues. For wind power applications, a more detailed review is done in Chapter 6, which encompasses disturbance mitigation through production facility design as well as through mitigation devices. Many of the devices listed here in Chapter 4 are primarily used for load protection, not in wind farms. This is not surprising since distributed generation and wind power are comparatively new additions to the power system. [9]

Most newly developed mitigation devices use power electronics. These are commonly referred to as Flexible AC Transmission Systems (FACTS) Devices (or Custom Power Devices when applied in the distribution system) or simply active mitigation devices. Names and abbreviations for specific device mentioned below may also vary somewhat. There is constant development within this category of mitigation devices, with new combinations, control systems etc. appearing frequently, permitting new application areas and higher efficiency. This review includes a range of active devices which represent the usual building blocks of FACTS, without claiming to include every variation of this popular theme. [2,5]

4.1. Voltage Dip & Short Interruption Mitigation

By changing the structure and/or operation of the power system, the frequency and severity of dips and interruption can be decreased. Also, choosing equipment with high tolerance will reduce vulnerability to dips and short interruptions. Apart from these measures, there is a wide range of mitigation devices for voltage dips and short interruptions which are reviewed below. Also, SVCs and STATCOMs (see Chapter 4.4) can be used for voltage dip mitigation. [3]

4.1.1. Motor-Generator Set (M-G Set)

The principle of a motor-generator set (M-G set) is that a motor powered by the supply is driving a generator powering the load (see Figure 8). Between the motor and the generator, on the same axis, are flywheels which can store and release rotational energy to compensate for voltage drops in the supply. The inertia of the flywheels keeps the load voltage steady even if the supply voltage drops, providing a so called ride-through time. This is the time the load can continue normal operation during a voltage dip or an interruption. [2,9]

Disadvantages of the M-G set include sometimes high noise levels and maintenance requirements, as well as the relatively large size of the equipment. Also, there are losses in all three machines and, because the ride-through depends on inertia, the frequency and voltage will drop continuously during ride-through. [2,9]

There are ways of alleviating the latter of the disadvantages. Special types of M-G sets use a so called written-pole motor instead of the generator in the set. This machine is a special synchronous generator which can produce constant 50 Hz-frequent power even as the machine slows. The polarity of the rotor's field poles is continually changed, changing the number of poles of the machine with each revolution. While the revolutions per minute are held above a certain value (by the flywheels' inertia) the power frequency will remain constant. This increases the ride-through time. Another way of compensating the voltage and frequency drops is by adding a rectifier followed by an inverter to the output of the generator. [9]

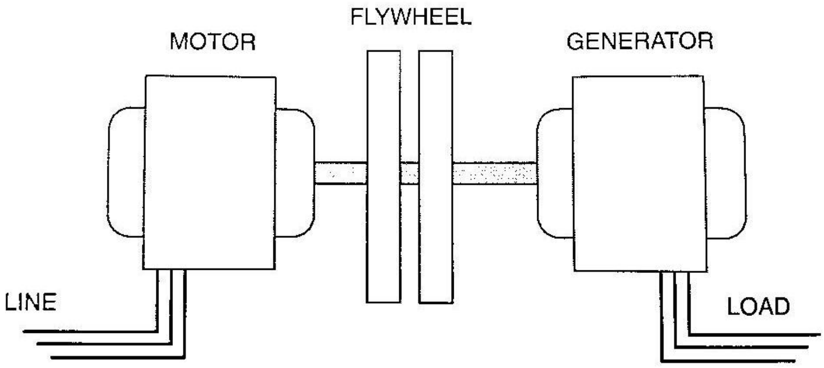

Figure 8. Block diagram of a typical M-G set with flywheel. [9]

4.1.2. Constant Voltage Transformer (CVT) & Magnetic Synthesizer
Constant voltage transformers (CVTs), also called ferroresonant transformers, are basically 1:1 transformers excited high on their saturation curves to provide an output voltage not significantly affected by input voltage variations. In practice a capacitor is needed on the output to achieve this highly saturated operating point (see Figure 9). [3]

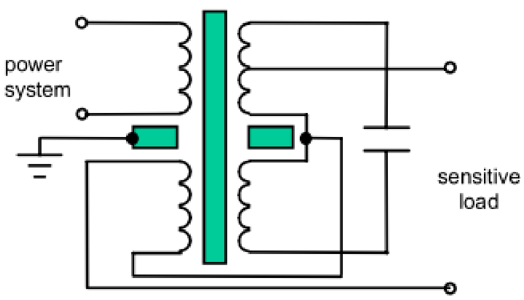

Figure 9. Typical circuit for a CVT. [3]

CVTs are most suited for protecting constant, low-power loads, whereas variable loads can cause problems due to the tuned circuit on the output. The CVT should have a considerably larger power rating than the load it is supplying for effective ride-through during severe voltage dips. The higher the loading of the CVT, the more limited the ride-through capability will be and if the CVT is overloaded the voltage can even collapse to zero. [9]

Magnetic synthesizers have the same basic operating principles as CVTs, but are always three-phase devices. Three-phase magnetics are used to improve voltage dip mitigation for three-phase loads. [9]

4.1.3. Static Transfer Switch (STS) & Fast Transfer Switch

A static transfer switch (STS) uses power electronics to switch between two independent power supplies. If there are two feeding lines available, connected to different substations, these can be interconnected with an STS to enable switching the load of one feeding line over to the other in case of a voltage dip on the first line.

An STS consists of two three-phase static switches. The static switches, in turn, each consist of two antiparallel thyristors per phase. Mechanical switches can be used instead of STSs, but even the fast transfer switch – the fastest mechanical alternative – is still several times slower than an STS. [2,9]

4.1.4. Uninterruptable Power Supply (UPS) System

Uninterruptable Power Supply (UPS) systems normally consist of a rectifier in series with an inverter, with an energy storage device of some sort shunt connected in between the two (see Figure 10). During normal operation the AC power from the supply is rectified to charge the energy storage device (when charging is needed) and during disturbances the DC power from the energy storage device is inverted to AC power to supply the load. [9]

There are three types of UPS systems with respect to how and when the switch in Figure 10 is operated. In on-line UPS systems the load is always fed through the UPS. The switch is a manual bypass switch, never closed during normal operation. This provides instantaneous reaction time, but also generates conversion losses. Standby UPS systems do not supply the load during normal operation, but are bypassed. The switch is an automatic transfer switch that switches to the UPS when a disturbance is detected. Hybrid UPS systems work in much the same way as standby UPS systems, but have a voltage regulator at the output instead of the automatic transfer switch to shorten the transfer time from the normal supply to the UPS. [9]

The energy storage device is normally a battery bank. However, there are possible alternatives like flywheel energy storage devices and superconducting magnetic energy storage (SMES) devices. Flywheel energy storage devices use high-speed flywheels to store rotational energy. These are usually operated in vacuum with magnetic bearings to reduce standby losses. This can be very size efficient and the continuous voltage drop (see Chapter 4.1.1) can be countered with control systems. SMES devices store energy in super cooled magnetic coils, which requires somewhat more advanced power electronics and control systems but provides faster energy delivery and faster recharge cycles. [9]

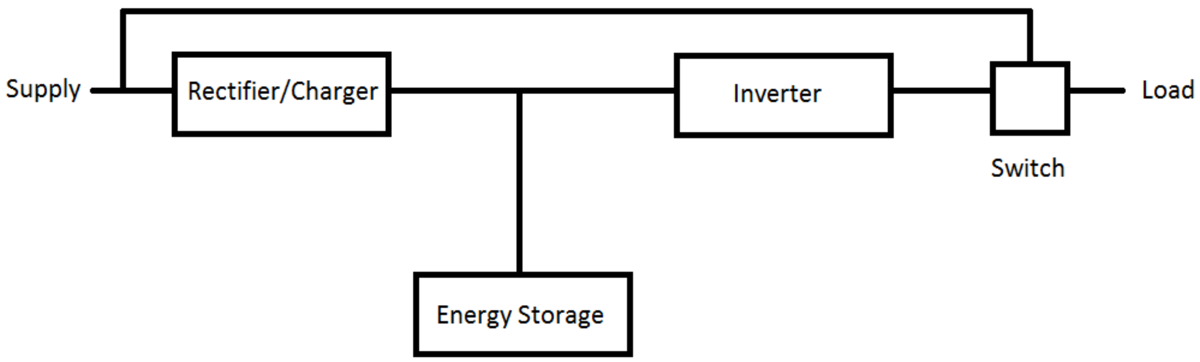

Figure 10. General block diagram of a UPS system.

4.1.5. Backup Stored Energy System (BSES)

Backup stored energy systems (BSESs), also called E-STATCOMs (see Chapter 4.4.2), are an alternative to UPS systems. Here the energy storage device (see Chapter 4.1.4) is shunt connected to the feeding line through a voltage source converter (VSC), which produces a variable magnitude and frequency three-phase voltage. A static switch (see Chapter 4.1.3) disconnects the primary supply when a disturbance is detected (see Figure 11). [3]

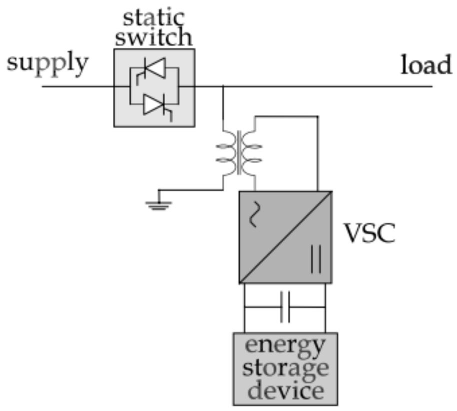

Figure 11. Diagram of a BSES system. [3]

4.1.6. Static Voltage Regulator (SVR)

A static voltage regulator (SVR) is a dedicated transformer equipped with electronic tap changers. The secondary winding is divided and thyristors connected to the winding segments change the turns ratio of the transformer to compensate for voltage dips from the supply. [3]

4.1.7. Static Series Compensator (SSC)

In the static series compensator, also called dynamic voltage restorer (DVR), an energy storage device (see Chapter 4.1.4) is connected in series with the feeding line through a VSC (contrary to the shunt connected BSES, see Chapter 4.1.5). The voltage injected from the SSC is added to the supply voltage to keep the load voltage steady (see Figure 12). [3]

If you combine the SSC with an STS (see Chapter 4.1.3) you can provide a steady load voltage during both severe dips and interruptions in the distribution system (which the STS handle well) and during dips in the transmission system (which the STS cannot handle, but the SSC handle well). [3]

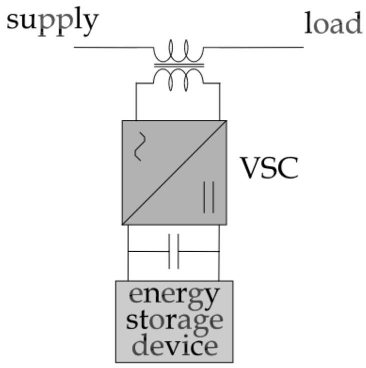

Figure 12. Diagram of a SSC system. [3]

4.1.8. Unified Power Quality Conditioner (UPQC)

If the energy storage device of an SSC is replaced with a shunt connected VSC connected to the feeding line upstream or downstream from (left or right of) the original series connected VSC, the resulting device is called a unified power quality conditioner (UPQC). The right-shunt configuration has proved superior in several operational aspects. [2,5]

The UPQC can be seen as a combination of a voltage source converter (injecting a series voltage v_c) and a current source converter (injecting a shunt current i_c). These converters have a shared DC link with energy storage capacitors. They are PWM-controlled through a UPQC control system. The design is completed with a low-pass and a high-pass filter and a series and a shunt transformer to electrically isolate the connections to the line (see Figure 13). [5]

The UPQC is a very versatile mitigation device. It can be used to mitigate waveform distortions of different types, voltage fluctuations (flicker), voltage dips and swells, as well as unbalance and even long-duration voltage variations. However, due to their high cost and often unnecessarily complicated structure compared to the problems in need of mitigation there are extremely few UPQCs actually being used today. [3,5]

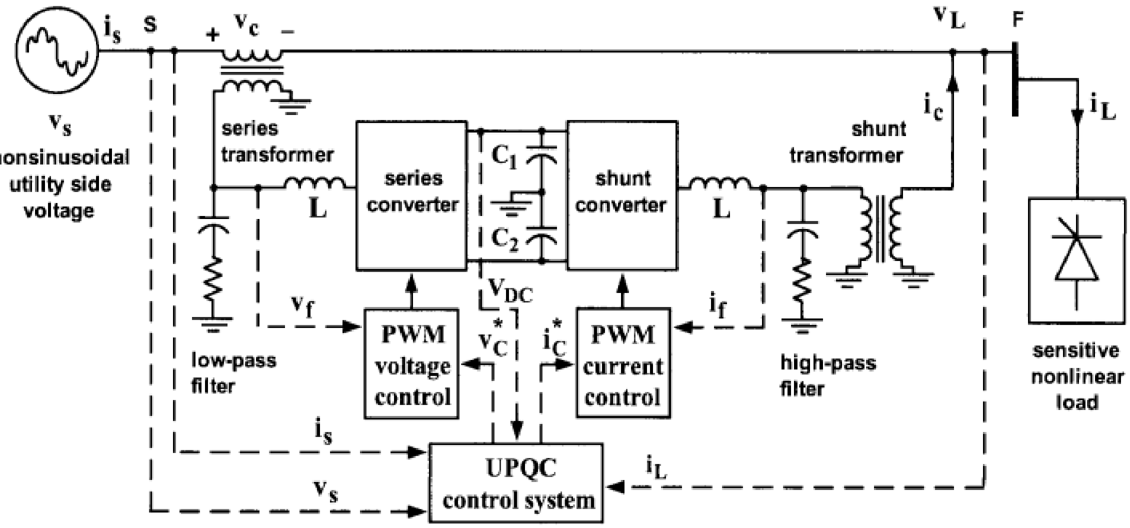

Figure 13. Detailed configuration of a right-shunt UPQC. [5]

4.2. Transients Mitigation

Impulsive and oscillatory transient overvoltages can be partly mitigated by grid design, for example by bonding grounds and preventing surge currents from flowing between grounds, but the following devices are also vital. These devices can also be combined into so called hybrid transient protectors to increase performance. An example of this is found in Figure 14.

4.2.1. Surge Arrester & Transient Voltage Surge Suppressor (TVSS)

Surge arresters and transient voltage surge suppressors (TVSSs) are more or less interchangeable terms, even though TVSSs are usually placed and adapted for use at load equipment. These shunt connected devices limit the maximum voltage between two points in a circuit. They can be divided into two subtypes: Crowbar devices and clamping devices. [9]

Crowbar devices, or gap-type devices, are open during normal operation and short-circuited during transient overvoltages. They usually consist of gaps filled with air or some other gas and during overvoltages an arc connects the two sides. The obvious disadvantage of crowbar devices is that the line voltage drops to zero during the transient overvoltage. [9]

Clamping devices are usually very nonlinear resistors (varistors) which during normal operation appear open because of their very high impedance. During transient overvoltages, however, their impedance drops rapidly with increasing voltage. The line voltage never drops below its value at the time when these devices start to conduct the surge current, ensuring no interruption of the load current (as opposed to crowbar devices). [9]

Clamping devices are sometimes called metal oxide varistors (MOVs), due to the fact that the newer ones are almost exclusively made from metal oxides, e. g. the very common and extremely nonlinear zinc oxide (ZnO). However, zener-diodes and varistors made of silicon carbide (SiC) can also be used. It is also possible to combine MOVs with gaps to create an instantaneous voltage drop at the beginning of a surge, but not all the way down to zero. These added gaps are almost necessary for the older SiC arresters, because SiC is not nonlinear enough in itself to provide cost effective overvoltage protection without them. [9]

4.2.2. Isolation Transformer & Low Impedance Power Conditioner (LIPC)

Isolation transformers are versatile power quality mitigation devices which among other things are good for limiting transient overvoltages. Low impedance power conditioners (LIPCs) are isolation transformers with low impedance and an output filter. LIPCs are not as good at low- to medium-frequent oscillatory transients, but are better at handling other disturbance types. [9]

4.2.3. Low-Pass Filter

Due to the often very high frequency content of impulsive and oscillatory transients, low-pass filters can be quite effective. These filters are often comprised of inductors in series with the line and shunt connected capacitors on either side of them (in a pi-circuit) or simply a series reactor and a shunt capacitor. [9]

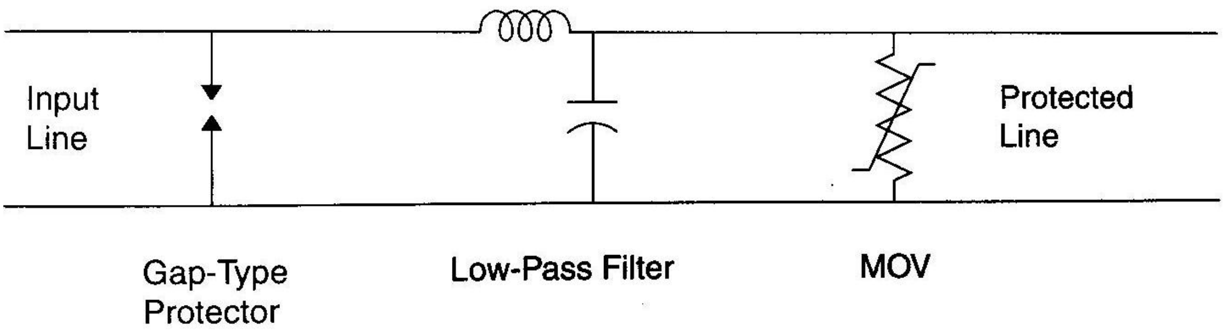

Figure 14. Hybrid transient protector. [9]

4.3. Waveform Distortion (Harmonics) Mitigation

Waveform distortion mitigation is usually focused on harmonics, mostly integer harmonics, since this is the most common type of waveform distortion. As previously mentioned the UPQC (see Chapter 4.1.8) can be used to mitigate many different types of waveform distortion. [9]

4.3.1. Zigzag Transformer

Zigzag transformers are basically wye-connected transformers with two interconnected winding halves per phase, the name stemming from the zigzag pattern formed by the positions of the interconnected winding halves. Zigzag transformers filter triplen harmonics from the neutral conductor, reducing the neutral current back towards the supply and preventing overload in the neutral conductor. The triplen harmonics are trapped in the transformer windings. For this to be effective the zigzag transformer needs to be placed close to the source of the harmonics. [9,10]

4.3.2. Isolation Transformer

Isolation transformers, especially if equipped with an electrostatic shield, can be quite effective in reducing electric noise, voltage notching and other waveform distortions as well as transients (see Chapter 4.2.2). This mitigation method works both ways; i. e. shields both the load from disturbances from the grid and the grid from disturbances from the load. [9]

4.3.3. Magnetic Synthesizer

Magnetic synthesizers using nonlinear chokes (inductors) to achieve line isolation produce an output voltage with a clean waveform and little harmonic distortion. This method also utilizes a zigzag transformer as part of its mechanism. [9]

4.3.4. Passive Filter

Filters consisting of passive components (mostly inductors and capacitors) can be tuned to filter out harmonic frequencies. The most common types are shunt passive filters which divert the harmonic currents away from the line. These filters come in many configurations and some can be tuned to divert specific harmonic frequencies. Normally a chain of LC-filters tuned to different frequencies plus a high-pass filter are used to provide a complete protection. [2,9]

There are also series passive filters, which basically consist of an inductor and a capacitor connected in parallel and series connected with the line. These filters are tuned to provide high impedance at certain harmonic frequencies to block them. Series passive filters are also usually used together with shunt passive filters to arrive at a complete protection. Series filters are less common than shunt filters because they need to be able to handle the whole line current as well as occurring over currents and series filters also have more losses associated with them than shunt filters. Also, low-pass filters can be used (see Chapter 4.2.3). [9]

Disadvantages of passive filters are their potential to of interacting adversely with the power system and the reactive power produced by included capacitors, which may not be desired. [9]

4.3.5. Active Filter

Active filters use power electronics to filter harmonics. The working principle of an active filter is as follows (see Figure 15): Current is stored in either an inductor or a capacitor. The line voltage or current is meticulously monitored to map the non-sinusoidal nature of the distorted waveform. The stored current is then injected through power electronics at the precisely right time instant and with the exact magnitude required to compensate for the harmonics in the waveforms. For example, a negative sequence (see Chapter 3.6.2.1) harmonic component can be counteracted by injection of a component with the same frequency and magnitude but the opposite phase rotation. Active filters are not susceptible to resonance and can work independently of system impedance. In addition they can target multiple harmonics at once by injecting current containing multiple frequency components. A fairly sophisticated control system is needed for active filters to work but such a control system can also be programmed to make the filters aid in reactive power compensation. [2,9,11]

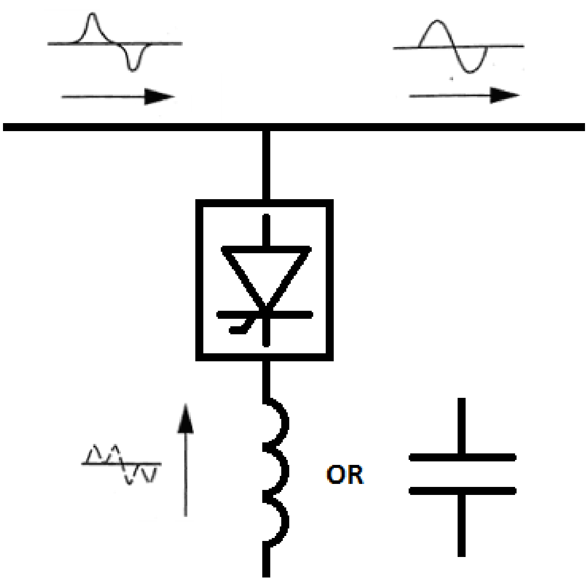

Figure 15. Principle operation of an active filter.

4.4. Voltage Fluctuation (Flicker) Mitigation

Voltage fluctuations in themselves cause little harm to the power system. Voltage fluctuation mitigation therefore tends to focus almost exclusively on flicker mitigation. There are two major methods for flicker mitigation, both primarily used for reactive power compensation but also for flicker mitigation. These two methods will be reviewed separately below, but there are also other methods available. Active filters can be tuned to reduce flicker. Reinforcement of the grid and careful selection of in-feed to arc furnaces prevent flicker from developing. Also, insertion of series devices such as capacitors, linear or saturable reactors or anti-parallel thyristors in series with a reactor can mitigate flicker. Furthermore and as previously mentioned, the UPQC can also be used for flicker mitigation (see Chapter 4.1.8). [3]

4.4.1. Static VAr Compensator (SVC)

Static VAr compensators (SVCs) use passive elements to generate and absorb reactive power. These passive elements usually consist of branches, one branch with a thyristor controllable reactor (TCR) and a number of thyristor switched capacitor (TSC) branches. It is also possible to have a TCR together with fixed capacitor banks or without capacitors altogether. The latter designs, along with branches with filters are more common for flicker mitigation purposes. In Figure 16 an example SVC with TCR, TSC and filter branches is displayed. A disadvantage of SVCs for flicker mitigation is their slow response time. [2,9]

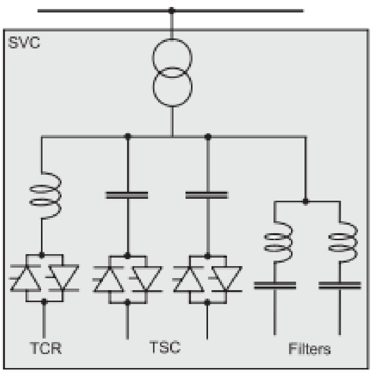

Figure 16. SVC with a TCR, two TSCs and filters. [3]

4.4.2. Static Synchronous Compensator (STATCOM)

The STATCOM (or D-STATCOM when applied to the distribution system) is the common name for a shunt connected, force-commutated (see Chapter 5.1.3), PWM-controlled VSC mounting IGBTs (possibly with an energy storage device behind it; see Figure 17). STATCOM is short for static synchronous compensator. The use of IGBTs – instead of GTOs which was common earlier – and PWM-control provides a fast response and makes the STATCOM suitable for mitigating fast disturbances such as voltage dips as well as flicker. These devices can generate and consume reactive power and an interesting feature is that they can also control the active power if the VSC is equipped with an energy storage device. [2,12]

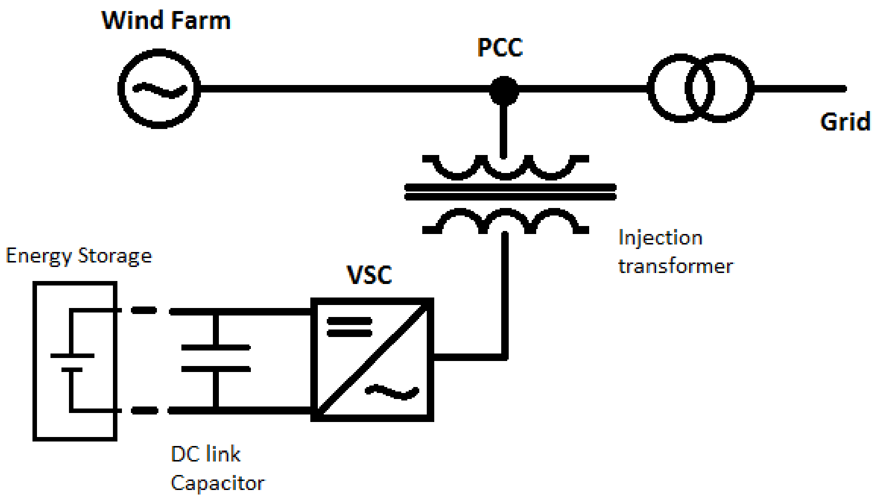

Figure 17. STATCOM with optional energy storage.

4.5.Voltage Swell Mitigation

Voltage swells are rare occurrences which normally do not require special mitigation. However, fast transfer switches and UPQCs (see Chapters 4.1.3 and 4.1.8 respectively) can be used for this purpose and other types of overvoltage mitigation devices mentioned in this review might provide protection against swells as well. [3]

4.6.Voltage/Current Unbalance Mitigation

SVCs and UPQCs (see Chapter 4.4.1 and 4.1.8 respectively) can be used to correct current unbalance by generating or absorbing different amounts of reactive power for different phases. SSCs (see Chapters 4.1.7) and UPQCs can mitigate voltage unbalance if an appropriate control system is used. The approach needs to be different for voltage and current unbalance, since adjusting the voltage requires a series device and current adjustment requires a shunt device (this is briefly explained when the UPQC is described in Chapters 4.1.8). [3]

4.7.Power Frequency Variation Mitigation

Power frequency disturbances are, as previously mentioned, caused by a difference between generation and consumption of active power. Therefore correcting that discrepancy mitigates power frequency disturbances. [5]

4.8.Long-Duration Voltage Variation Mitigation

Long-duration voltage variations can be handled in many different ways. Tap-changing transformers, i. e. transformers with changeable turns ratios, are commonly used to correct under and overvoltages. Also, the following previously mentioned isolation devices can provide mitigation to a certain extent for most long-duration voltage variations: M-G sets, CVTs, magnetic synthesizers, UPS systems, SVRs and UPQCs (see Chapter 4.1). [9]

In addition to over mentioned mitigation methods, various forms of impedance compensation devices can be used for long-duration voltage variation mitigation. These include shunt capacitors installed at system buses and series capacitors on long lines. SVCs, though slow with respect to flicker mitigation (see Chapter 4.4.1), are also well-suited for mitigation of these slower long-duration voltage variation. [2,9]

5. Wind Power, A Brief Introduction

A modern wind turbine consists of the following parts: A tower, a rotor and a nacelle. The nacelle contains the drive train, the generator and often power electronics, protection systems, communication systems etc. Then, there is a yaw system used to steer the rotor in response to wind direction changes. There can also be a blade pitch adjustment system used to influence the rotor torque and/or help with pitch-control (see below) by rotating the blades around their longitudinal axes. This list of components only applies to horizontal axis turbines – which are overwhelmingly more common than vertical axis turbines. The most common types of horizontal axis wind turbines are reviewed in Chapter 5.1. [13,14]

Most horizontal axis turbines have three rotor blades (see cover picture). They utilize the force of lift of the wind on the rotor blades to produce rotation. The blades are shaped so that an overpressure is created on the underside of the blade and an underpressure above it. This lifts the blade and starts rotation. [14]

Vertical axis turbines, such as Darrieus and H-Darrieus (see Figure 18) types, exist but have not as of now been very successful. They cannot generate as much power as horizontal axis turbines, but can be built very small. Experiments are therefore being conducted regarding their suitability for small-scale urban wind power generation systems, e. g. placed on roof tops of apartment buildings. [8,14]

Figure 18. H-Darrieus type small vertical axis wind turbine. [15]

The purpose of the wind turbine is the conversion of the kinetic energy in the air into electrical power. Equation 1 shows the formula for the power (P) contained in the wind moving through an area (A) perpendicular to the wind velocity (ν_a); ρ is the air density. [13,14]

$$P = \frac{1}{2} * \rho * A * \nu_a^3 \qquad (1)$$

The percentage of this wind power P that a wind turbine can capture and convert into mechanical rotational power is given by the power coefficient c_p, which has a theoretical upper limit of 59.3 %. (At least 40.7 % of the kinetic energy must remain in the wind for the air not to start blocking the rotor instead of moving on.) The mechanical power is then converted into electrical power through the drive train and the generator. [8,13,14]

The withstand strength to mechanical loads is the key design parameter for wind turbines. An example is that using three blades per rotor is obviously more expensive than using two. However, most wind turbines still have three blades even though it is completely possible to design a two-blade rotor. This is because two-bladed wind turbines must operate at higher rotational speeds and therefore the two blades need to be lighter and stiffer – which means more expensive –, so factoring in the mechanical withstand strength leads to three-bladed rotors being superior after all. [13]

The turbine must somehow be kept from rotating too fast. This can be accomplished by designing the blades to either spill the extra energy or go into an aerodynamic stall above a certain wind speed – these methods are called pitch-control and stall-regulation respectively. The turbine also has a cut-in wind speed, i. e. a lowest wind speed at which it can generate power efficiently. The turbine is only started if the wind speed exceeds the cut-in wind speed. [13,14]

The development in the wind power sector has been rapid these last few years, with advances in both new turbine types (e. g. gearless synchronous generator turbines [16] and transverse flux machine turbines [17]) and improvements of existing designs to construct larger and more efficient wind power plants. Taller and higher power wind turbines can produce more stable power because of the higher wind speeds and lesser turbulence at higher altitudes. Today, 2 - 4 MW turbines are very common and 5 - 6 MW turbines are available and beginning to increase in numbers. The development has also gone towards larger wind farms and therefore connections at higher voltage levels. Many wind farms are today being connected at medium voltage levels and the largest ones even at the transmission level. [8]

Grouping wind turbines to form wind farms has several advantages. Firstly, power generation variations on a short time-scale from individual turbines (e. g. due to turbulence or wind gusts) can be smoothed out to a stable average. Secondly, you have the possibility of mixing cheap turbine types (fixed-speed turbines, see Chapter 5.1.1) with more controllable types (variable-speed turbines, see Chapters 5.1.2 and 5.1.3) to more cost effectively control the wind turbines and also reduce power quality disturbances. Wind farms also allow for centralization of both disturbance mitigation and grid connection equipment, i. e. you can use just one or a few devices for a whole wind farm to achieve these aims. [8,18]

The voltage level of modern wind turbines is usually 690 V or 400 V. Each turbine is then equipped with a transformer to transform the voltage to the main voltage level of the wind farm (generally in the medium voltage range, e. g. 10 kV). At this voltage level cables connect the turbines radially to a common point. Mitigation devices can be placed at this point, or at the individual turbines. After the common point and just before the point of common coupling (PCC), where the wind farm is connected to the grid, a larger transformer transforms the voltage to match the voltage level of the grid. For large wind farms the PCC usually consists of a substation. [8,18,19]

5.1. Wind Turbine Types

There are three basic types of wind turbines being used today, all of them horizontal axis turbines, which are reviewed below. These three types are used to about equal extent in the power system. This should, however, not be misinterpreted as though all three types are being built to an equal extent. Up until around a decade ago fixed-speed turbines (see Chapter 5.1.1) were dominant because they are cheap and simple in their design – and further back it was the only type available of the three. At present, the fixed-speed turbine type and the narrow range variable-speed turbine type with variable rotor resistances (see Chapters 5.1.1 and 5.1.2 respectively) are almost never produced, except in very small sizes. The DFIG subtype of narrow range variable-speed turbines (see Chapters 5.1.2) was very common during a period when fixed-speed turbines were phased out, but now DFIGs are almost phased out as well. Today, broad range variable-speed turbines (see Chapters 5.1.3) are the overwhelmingly most commonly built types. These types are more controllable and can therefore be made more efficient. The three types cause different power quality disturbances, but all wind turbines produce (long-duration) voltage variations due to the intermittent properties of wind power. [18,20,21,22,23,24]

5.1.1. Fixed-Speed Turbines

Fixed-speed turbines use induction generators with the usual closed-loop rotor windings. This design means the turbine is constructed for maximum efficiency at *one* speed. However, it is common enabling the stator winding to change between four and six poles to provide two efficient speeds instead of one. Between the rotor and the generator a gearbox is placed due to the much higher rotational speed of the generator compared to the rotor. The rotor speed is fixed and set by the ratio of the gearbox and the number of poles in the generator. [13,18]

The generator is connected directly to the grid; preferably through a soft starter to avoid high inrush currents (see Figure 19). Also, shunt capacitor banks are needed to compensate for the reactive power consumption of the generator, since reactive power control is not possible for fixed-speed turbines. Major advantages of fixed-speed turbines are low cost, simple and robust design and low maintenance requirements. [13]

Whenever a rotor blade passes the tower it comes into the tower shadow. For fixed-speed turbines this results in voltage fluctuations which in turn can cause flicker. The tower shadow effect is due to the facts that as the three blades rotate their collective altitude changes. Since wind speeds are higher at higher altitudes this means a varying wind speed average resulting in a varying power production. Also, when the wind hits the tower turbulence is created. [8,14]

Voltage dips should not be caused by fixed-speed turbines if a soft starter is installed and used properly. Fixed-speed turbines do also not under normal conditions produce harmonics. When switching the capacitor banks on or off oscillating transients may occur. [20]

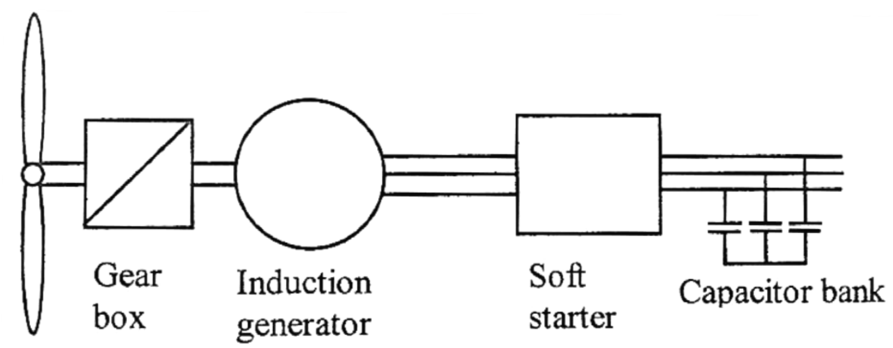

Figure 19. Fixed-speed wind turbine with soft starter and capacitor bank. [13]

5.1.2. Narrow Range Variable-Speed Turbines

Two arrangements are possible for narrow range variable-speed turbines. Firstly, there is the more common doubly-fed induction generator (DFIG) where the rotor winding is fed through a converter (see Figure 20). Then there is also a type identical to the fixed-speed turbine except for its variable rotor resistances, which enable speed variation through variation of the slip. A gearbox is required for both of these arrangements and the turbines often have four stator poles, just as for the fixed-speed turbines. These two topologies allow the generator frequency to differ from that of the grid, within a narrow range. [13,16,18]

DFIGs have been the most common of the narrow range variable-speed turbine types in recent years. DFIGs have the advantage over broad range variable-speed turbines of being less expensive, since their converters can be dimensioned not after the power rating of the entire turbine but the power needs of the rotor only. DFIGs have also had the advantage of being more similar to fixed-speed turbines, which made them more attractive during a transitional period. Lately, however, the DFIGs have been largely replaced by the more controllable broad range variable-speed turbines. [13,14, 21,22,23,24]

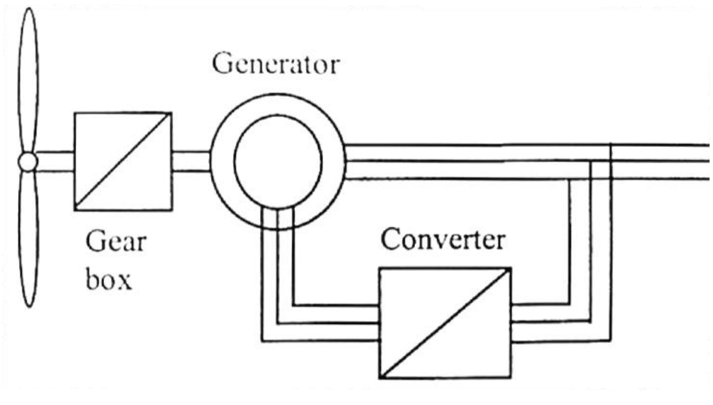

Figure 20. Narrow range variable-speed wind turbine with doubly-fed generator. [13]

Depending on the choice of turbine arrangement the disturbances caused by narrow range variable-speed turbines may closely resemble either fixed-speed turbines (variable rotor resistances) or broad range variable-speed turbines (DFIG) (see Chapters 5.1.1 and 5.1.3 respectively). However, both arrangements can counteract the tower shadow effect to a certain degree and thereby avoid flicker emissions. [8,13]

5.1.3. Broad Range Variable-Speed Turbines

Broad range variable-speed turbines, or full-converter turbines, use frequency converters between the generator and the grid (see Figure 21) where the voltage is first rectified and then inverted to match the magnitude and frequency of the grid. This makes them very flexible, able to draw rated power from the wind at a broad range of wind speeds. This turbine type has until a few years ago consisted solely of induction generators with gearboxes and this is still the most common topology. However, the frequency converter also enables the use of synchronous generators. If a large diameter, multi-pole synchronous generator is used this eliminates the need for a gearbox and makes a more compact nacelle possible. [13,18,24]

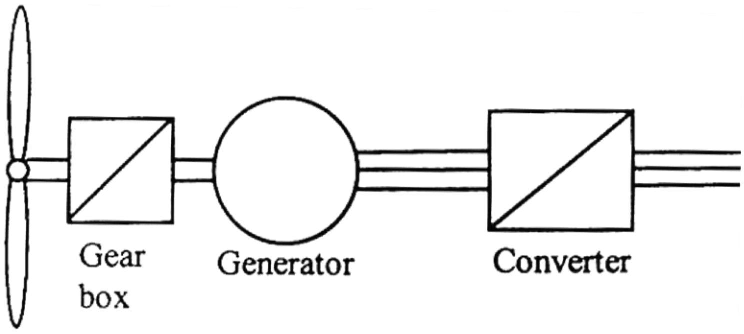

Figure 21. Broad range variable-speed wind turbine with gearbox. [13]

Turbines with induction generators commonly have a power rating in the range 2 - 4 MW today. Using synchronous generators enables production of turbines with even higher power ratings without the nacelle becoming too large to transport. Turbines with synchronous generators rated at 6 MW are currently operated in several locations and because of the compact nacelle design these turbines weigh about the same as 3.6 MW induction generator turbines. The development is therefore towards synchronous generator type full-converter turbines replacing the induction generator type, especially for large turbine sizes. [22,24]

There are two types of inverters which can be used in the frequency converter. Line-commutated inverters are thyristor switched and therefore require grid connection to operate. Force-commutated (or self-commutated) inverters usually use PWM-controlled IGBTs and can be controlled independently of the grid. Both inverter types can effectively counteract the tower shadow effect and prevent high inrush currents. Therefore broad range variable-speed turbines create no flicker emissions and cause no voltage dips under normal operation. [13]

The two inverter types both produce harmonics, but different frequencies. This makes the choice of inverter relevant for the choice of harmonics mitigation devices. The force-commutated inverter will produce higher frequency integer harmonics than the line-commutated inverter, but the force-commutated inverter also produces interharmonics. The latter type is the more common and the most versatile. With force-commutated inverters you can choose through the software (to a degree) which harmonic frequencies will be created. [13,20]

6. Wind Farms and Power Quality Disturbances

The two major disturbance types that are always considered when constructing wind farms are flicker and harmonics. Also, strict limits are usually set for unbalance and rapid voltage changes. Beyond these disturbance types wind farms are of course required to comply with general power quality rules including withstand strength to the other power quality disturbance types dealt with in the subchapters below (see Chapter 6.3). [21,22,23]

When dealing with power quality mitigation in wind farms you must distinguish between external and internal mitigation. The terms internal and external are with respect to the turbine, not the wind farm. External mitigation devices are almost exclusively passive filters in Sweden and are applied outside the turbines but often within the wind farm, usually at the PCC, to compensate for power quality problems that were unforeseen or too severe for the internal mitigation devices to handle. The internal mitigation devices are the primary mitigation devices and are placed inside the converters of full-converter turbines – which are the overwhelmingly most commonly built turbine types today. They also consist predominantly of passive filters but the major turbine manufacturers outfit these filters with power electronics to be able to change the filter parameters. This is done because the flexibility this offers is necessary to be able to manufacture one turbine model for sale in many different markets (countries) with different power quality demands. When extreme requirements are set for a wind farm additional passive filters are sometimes added in sockets in the converters to improve mitigation. However, for this to be accepted by the manufacturer the network owner making these demands has to provide adequate cause for the stricter limits. Smaller manufacturers focused on one market might work primarily with passive filters with unchangeable properties because of their cheaper and simpler design. [21,22,23,24]

Passive filters, both for internal and external mitigation, will be described in the harmonics subchapter (see Chapter 6.2.5), because harmonics are what they mainly mitigate. Information about internal mitigation devices is restricted by the turbine manufacturers due to secrecy policies and therefore the description of these devices – concerning mainly the power electronics used to change the filter parameters – will unfortunately be very limited. [24]

The emission rules are relatively strict in Sweden and have been for a long time (even though there have historically existed loop holes and blind spots in the regulations and remnants of these may still exist). There is a continuous process to improve the rules at all levels, from the IEC down to individual Swedish network owners. For example, stricter Swedish laws regarding the withstand strength of wind farms (where the Swedish rules have been generous in relation to other European countries) are expected within a couple of years and the IEC emission limits for harmonics have been sharpened the last few years in response to the recent increased presence of nonlinear loads and power electronics in the power system. [9,13,21,22,23]

In the subchapters below the following classification system for voltage levels is used, defined through the nominal voltage U_n: A low voltage (LV) is $U_n \leq 1$ kV, a medium voltage (MV) is 1 kV < $U_n \leq 36$ kV, a high voltage (HV) is 36 kV < $U_n \leq 150$ kV, and an ultra-high voltage (UHV) is U_n > 150 kV. This classification is based on a division found in the Swedish Standard (SS-EN 50160), but is not an official classification system. [2]

Since the focus of this report is on large wind power production facilities the focus will be on connection voltages at HV and UHV voltage levels, which also are the most common voltage levels for new wind farms to be connected to today. At Vattenfall in Sweden, for example, wind farms are often connected to the HV grid for power ratings of 15 MW and above, which with the currently common turbine size of 2 - 4 MW translates to only 4 - 8 wind turbines. Most wind farms being constructed today are at least this big. To be allowed to connect a wind farm to the Swedish transmission system (220 - 400 kV) the solitary network owner at the UHV level in Sweden, Svenska Kraftnät (SvK), requires a power rating of no less than 100 MW, but usually wind farms connected there are even larger than that. (Wind farms with power ratings of several hundred MW exist.) Exceptions can be made under special circumstances. [22,23,24,25]

When a new wind farm is under planning an application must be sent to the network owner whose grid the wind farm is to be connected to. The network owner will then have certain demands regarding areas such as safety and power quality which must be fulfilled for the wind farm to be allowed to be connected to their grid. The network owner, being responsible for the power quality of their part of the power system, requires the wind farm operator to sign a contract dictating the highest levels of the different power quality disturbance types the wind farm is allowed to produce and must be able to withstand. The network owner is responsible for setting these levels to ensure that the power quality at the PCC is within its allowed limits. The limits for the PCC, in turn, are set to ensure the power quality of a larger part of the grid and so on. [22,23]

There are two possible methods of setting the allowed levels for the wind farm. The first is to have general rules that apply equally to all producers and consumers connected to that part of the grid. The second method is to calculate emission quotas for each installation. It may vary from network owner to network owner which method is used for which of the power quality disturbance types. However, the second method is generally used for harmonics and flicker from large wind farms. [22,23]

The second method is performed according to the following principle: There are absolute upper limits of the emission levels for the different voltage levels in the power system called target limits (TL; sv: Målgränser). All equipment in the power system must be able to withstand disturbance levels as high as that. Then there are stricter limits called planning levels (PL; sv: Planeringsnivåer) which are used for dimensioning the grid, setting general emission limits, and distributing emission quotas to the customers of the network owners. When emission quotas are to be calculated for a new wind farm the existing levels of emissions must first be measured and then a part of the remaining capacity within the PL is assigned to the new wind farm. Usually the assessment of what emission quotas to assign to a certain wind farm is based on its power rating compared to the capacity of the grid, as well as on prognoses of the disturbance emissions of the wind farm. [22,23]

The prognoses should take into account the following: The normal operating mode today, all possible modes of operation during faults and maintenance today and also all corresponding modes of operation in the future for the duration of the estimated life span of the wind farm. Naturally, assumptions and simplifications need to be made to be able to practically perform these prognoses. They are based on impedance calculations of *all* parts of the entire power system. So called impedance sectors can be used for these calculations, where the impedances of all parts of the system are represented by intervals of magnitude and phase angle. Sometimes standard values are used or whole parts of the system are lumped together into one impedance sector. The result of the prognoses is a, sometimes rough, estimate of the impedance of the entire system. [23]

The system impedance value produced from the prognoses is given to the wind farm operator along with emission quotas expressed in voltage terms for use in calculations of disturbance emission levels from the wind turbines. The impedance value is needed since the operator’s emission calculations are based on values for drawn current, not on voltage values. The calculations required of the operator are also very complex since, to obtain a complete view of the emissions that might at some point be caused by the wind farm, every combination of wind turbines operating at every possible operating point (wind speed) must be considered including all operational modes where one or several turbines are off-line. The permutations are too vast for it to be practically possible to provide a complete picture, hence the operator must judge which operational modes to select for calculations to be performed on. The operator’s results must then be approved by the network owner and later verified by measurements after the wind farm is connected to the grid. These measurements are, however, only as complete as the wind conditions and operational status of the wind farm during the measurement period permits. For example, if all turbines are functioning well and are all operated at the same time during the entire measurement period the calculation results of the emission levels produced when some turbines are off-line will not in fact be verified. The self-imposed Swedish electric power industry standards AMP [26] and ASP [27] – describing what must be considered when connecting small and large wind farms respectively to the grid – contain typical values from measurements of power quality disturbances in wind farms, to be used if for some reason no appropriate measurement data is available. [22,23]

The PL, unlike the TL, is dependent on the strength of the grid. (A common way of measuring the strength of a grid is by using the short-circuit power and a measurement of how well a certain grid can support a certain wind farm is given by the short-circuit ratio, which is a ratio between the short-circuit power of the grid and the rated apparent power of the wind farm.) This dependency means that the PL can vary between different parts of the grid within the same voltage level and the existing levels of emissions, of course, also vary from place to place. The effect of this is that the same wind farm placed in two different locations at the same voltage level may be assigned different emission quotas. However, the connection fee will remain the same (as long as the network owner is the same and no strengthening of the grid is required for connection to be possible) since this fee is usually based on the power rating of the wind farm. The choice of location for a wind farm can therefore be important for this reason as well as of course for other reasons, such as the properties of the wind.

Sometimes general PL values found in the Swedish Standard or the guidelines of SvK are stated in this report, but geographic variations may still exist. [22,23,28,29]

The power quality rules of the Swedish Standard are sometimes considered too generous by network owners and their customers. For example, allowing ±10 % voltage variations at the 400 V level does not provide high enough power quality to satisfy most customers. This results in some network owners having stricter demands than the Swedish Standard requires for some power quality disturbance types. [22]

When the calculations of the emission levels are done the internal filters of the converters are adjusted to keep the emissions within allowed limits. The wind farm owner must then decide if the power quality level should be made higher than required. Here the cost of having high power quality – higher power quality means higher losses – is weighed against the potential competitive edge it provides. Usually the required levels are followed. Adjusting the power quality to match emission quotas is done primarily by adjusting the internal mitigation devices (filters). [24]

If, when the adjustments are done, external mitigation devices are required for some disturbance types to fulfill the emission quotas there is a general philosophy in the Swedish electric power industry to try to choose as simple and robust a mitigation method as possible. The life span of power system equipment is so long and reliability so important that simplicity and robustness take precedence over flexibility and ease-of-use when choosing mitigation devices. This is a major reason why active power quality mitigation devices – especially based on advanced power electronics and with complicated control systems – are extremely rare in the Swedish power even in new installations. More complicated devices have more possible sources or error and are harder to troubleshoot. Another reason is that active methods are still usually much more expensive than their passive counterparts. Furthermore, the rapid development in the field of active mitigation devices can cast doubt on whether it will be possible to find spare parts and maintenance personnel for these devices in a couple of decades or if the current models will all be obsolete by then. Passive methods have in many cases already existed for decades and will probably continue to exist largely unchanged for several more decades. Choosing such methods is therefore considered a safer investment and a more easily justifiable one in the very long time span which must be considered for investments in the power system. [21,23]

6.1. Voltage Fluctuations (Flicker) in Wind Farms

Voltage fluctuations in wind turbines can have the following causes: Changes in wind speed, the tower shadow effect, blade asymmetry, blade bending and skewing, and tower oscillation. The tower shadow effect and wind speed changes are the two most significant causes of flicker. The tower shadow effect will cause a slight voltage drop every time a rotor blade passes the tower; i. e. three times per revolution of the rotor for three-bladed turbines, which is why the term 3p oscillations is used. The remaining possible sources are related to design issues of specific components, such as the rotor blades. As for most voltage variations, the influence of voltage fluctuations and the severity of the resulting flicker are dependent on the strength of the grid. If the grid is weak, i. e. has a high susceptibility to voltage changes in production facilities and loads, the same voltage fluctuations will be more noticeable than in a strong grid. [8,9,13,14]

Quantifying flicker is difficult – since flicker severity is a matter of perception – and usually involves a lot of steps of measurements and analyses. Brief descriptions will follow of one general method for measurements of the flicker level at a certain point on the grid as well as methods directly related to wind power applications. For further details about the measurement procedures I refer to the standards SS-EN 61000-4-15 (about the IEC flicker meter) and SS-EN 61400-21 [30] (about flicker measurements in wind farms). [9,13]

The IEC has a general standardized measurement method for flicker severity based on a series of voltage and current measurements at a certain point in a power system. There are IEC flicker meters which perform these measurements according to the official model. The flicker meter performs five steps of measurements and analyses to produce a flicker severity value: [9]

1. The input voltage and current waveforms are scaled to an internal reference level.
2. The input is demodulated; i. e. the voltage fluctuation is separated from the carrier signal.
3. The signal is filtered to remove unwanted frequencies produced by the demodulator.
4. The signal is adjusted to compensate for the human perception of flicker. This is necessary since the brain's threshold for flicker perception varies with the flicker frequency. A level of 1.0 in the output from Step 4 corresponds to the level at which the flicker becomes perceptible. There is a flicker curve that illustrates which relative voltage magnitude of the flicker the 1.0 level corresponds to for different flicker frequencies (see Figure 22). (Generally flicker with frequencies around 10 Hz is noticeable at the lowest magnitudes.)
5. The data for the instantaneous flicker from Step 4 is processed statistically to produce a probability function for the flicker severity at the measuring point. [9,13]

Two concrete values, a short-term (P_{ST}) and a long-term (P_{LT}) flicker severity value, are used to set the allowed limits for flicker emission. In the general case the calculations of these values are based on the probability function produced by the flicker meter. A general formula for P_{ST} is found in Equation 2, where $P_{0.1}$, P_{1s}, P_{3s}, P_{10s} and P_{50s} are the flicker levels exceeded 0.1, 1, 2, 10 and 50 percent of the time respectively. P_{ST} is based on measurement data from a period of 10 min. The formula for calculating P_{LT} based on P_{ST} is found in Equation 3. P_{LT} is based on 12 P_{ST} values; i. e. P_{LT} is based on 2 h of data. [2,9]

At the UHV level of the Swedish power system the flicker TL is that 95 % of the flicker emissions during a week shall fulfill $P_{ST} \leq 1.5$ and $P_{LT} \leq 1.25$. The corresponding PL values are generally around $P_{ST} \leq 1.0$ and $P_{LT} \leq 0.8$. The long-term TL value for flicker at the HV level is $P_{LT} \leq 1.0$. [2,28,29]

Here follows an example of how to interpret the limits: If a wind turbine with three blades rotates at 30 revolutions per minute (i. e. 0.5 revolutions per second) the tower shadow effect will cause 3p oscillations at a frequency of 1.5 Hz. From Figure 22 it can be observed that the relative voltage magnitude of the voltage fluctuations causing this flicker disturbance must be below roughly 0.65 % to be below P_{ST} = 1.0; i. e. not be perceivable. Then the flicker will comply with the short-term PL for the UHV level. This is of course assuming no other flicker emissions are present in the system. [8,27]

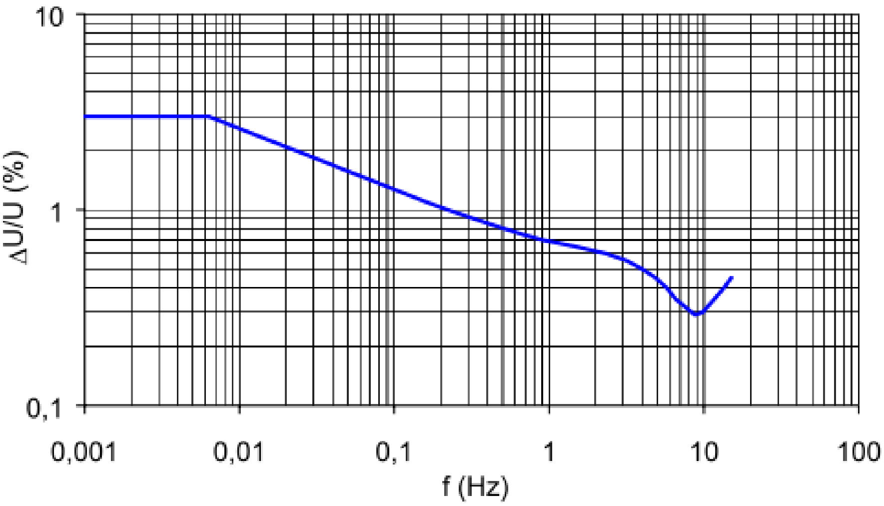

Figure 22. Flicker curve showing the limit for perceivable levels of flicker at different frequencies. [27]

$$P_{ST} = \sqrt{0.0314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s}} \qquad (2)$$

$$P_{LT} = \sqrt[3]{\frac{\sum_{i=1}^{12} P_{ST,i}^3}{12}} \qquad (3)$$

The general formula for P_{ST} in Equation 2 is, however, not used for measurements in wind farms. The methods for wind farms are detailed in SS-EN 61400-21 [30]. Here flicker measurements are divided into two groups: Continuous operation and switching operations. Both types of flicker are problematic almost exclusively when using fixed-speed turbines. [13,21,23,30]

The measurement method for continuous operation involves using a fictitious reference grid to arrive at flicker emission values for the wind turbines without the measurements being influenced by flicker from other sources connected to the same power system. Flicker coefficients ($c(\psi_k,\nu_a)$) are determined for each wind turbine based on P_{ST} values calculated for the fictitious grid ($P_{ST,fic}$), the rated apparent power of the wind turbine (S_n) and the apparent short-circuit power of the fictitious grid ($S_{k,fic}$) (see Equation 4). The $P_{ST,fic}$ values are determined for different grid angles (ψ_k) and at different wind velocities (ν_a). The grid angle is acquired from Equation 5, where X_k is the grid reactance and R_k is the grid resistance. [13,30]

$$c(\psi_k, v_a) = P_{ST,fic} * \frac{S_{k,fic}}{S_n} \tag{4}$$

$$\psi_k = \arctan\left(\frac{X_k}{R_k}\right) \tag{5}$$

The spread of flicker coefficients for each turbine resulting from the above calculations are processed probabilistically to arrive at one value per turbine. Then the P_{ST} value for each turbine can be calculated using Equation 6, where S_k is the short-circuit power of the actual grid (not the fictitious grid) at the PCC. The P_{ST} value for the entire wind farm ($P_{ST\,\Sigma}$) can then be calculated from Equation 7, where $P_{ST,i}$ is the P_{ST} value for the i^{th} turbine. The P_{LT} for the wind farm is calculated from Equation 3 using 12 $P_{ST\,\Sigma}$ values. [13,30]

$$P_{ST} = c(\psi_k, v_a) * \frac{S_n}{S_k} \tag{6}$$

$$P_{ST\,\Sigma} = \sqrt{\sum_i P_{ST,i}^2} \tag{7}$$

Switching operations – including startup at cut-in wind speed, startup at rated wind speed or higher, and switching between generators – can also produce flicker disturbances. Here the standard SS-EN 61400-21 details how to determine the voltage change factor ($k_u(\psi_k)$) and the flicker step factor ($k_f(\psi_k)$) for different grid angles (ψ_k) through measurements, simulations and calculations. These steps also involve using a fictitious grid and are performed for a scenario with maximum possible switching events per 10 min period (N_{10m}) for P_{ST} calculations, and per 120 min period (N_{120m}) for P_{LT} calculations. [13,30]

In Equation 8 and Equation 9 the formulas for P_{ST} and P_{LT} respectively for a single wind turbine can be found. The total P_{ST} ($P_{ST\,\Sigma}$) and P_{LT} ($P_{LT\,\Sigma}$) values for the wind farm are then calculated by simply adding the contributions from all connected wind turbines. The voltage change factor ($k_u(\psi_k)$) can be used to calculate the relative voltage magnitude change caused by a single switching operation of a wind turbine. [13,30]

$$P_{ST} = 18 * N_{10m}^{0.31} * k_f(\psi_k) * \frac{S_n}{S_k} \tag{8}$$

$$P_{LT} = 8 * N_{120m}^{0.31} * k_f(\psi_k) * \frac{S_n}{S_k} \tag{9}$$

PL values at the HV level and below are set by the network owners (of which there are several at this level unlike at the UHV level) and can therefore vary. What flicker emissions are allowed from a specific large wind farm is, as previously mentioned, usually decided by calculating an emission quota. In AMP [25] and ASP [26] there are general emission limits which can be used if the network owner decides to use a simpler process and/or the wind farm is not large enough to warrant calculation of specific emission quotas. These emission limits restrict flicker emissions from one source to $P_{ST} \leq 0.35$ and $P_{LT} \leq 0.25$ for wind farms connected to distribution networks and $P_{LT} \leq 0.10$ for wind farms connected to regional networks. The reason for the much stricter limit at the regional level is that flicker disturbances propagate very easily from high voltage levels all the way through to the end-users. [21,22,23,26,27]

Flicker is currently not a big problem in the Swedish power system. Emissions are usually within allowed limits without having to employ external mitigation devices for flicker. This because, as previously mentioned, flicker is mostly a problem caused by fixed-speed wind turbines whereas the predominant turbine types being constructed today are full-converter turbines, which have internal flicker mitigation possibilities in their converters. Because of the difficulties associated with quantifying flicker, measurements can sometimes indicate problems which are not felt by any of the parties involved in the power system. Since flicker is in fact only a problem when perceived, the emission limits of flicker may therefore not always be as rigidly followed as limits for other power quality disturbances. [13,21,22,23,24]

6.2. Harmonics in Wind Farms

Harmonics in wind farms are mostly caused by power electronic converters. This means harmonics are primarily a problem for the converter-fed turbine types, DFIGs and full-converter wind turbines. This, in turn, makes harmonics a much more pressing concern than flicker which, as previously mentioned, is mostly caused by fixed-speed turbines. [21,22,23,24]

6.2.1. Converter Types

Converters are central to the discussion of harmonics and therefore the different types and components of converters will now be described in more detail: Converters can be divided into direct and indirect converters. Since only three-phase generators are used in wind turbines, all converters are also three-phase. Direct converters consist of an AC frequency converter (AC/AC converter) with two antiparallel power conversion bridges per phase to facilitate conversion in both directions. Indirect converters are comprised of a rectifier, a DC link and an inverter. This setup is today the norm for use in wind turbines. The DC link can be equipped either with a shunt capacitor to achieve constant voltage – making the converter a VSC – or with a series inductor to provide constant current – making the converter a CSC (current source converter; see Figure 23). The inductor or capacitor is needed to facilitate the energy transfer in the semiconductor bridges. Also, the larger the inductor or capacitor being used, the smaller the ripple in the DC current will be. Since the grid is usually inductive, the CSC is the most common because it just needs to amplify the already existing appearance to the generator of having a large inductive load. [14,31]

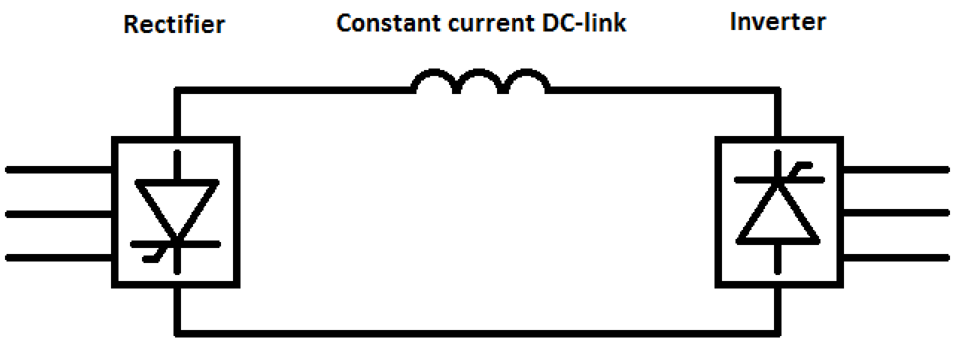

Figure 23. Basic model of a CSC.

The rectifier can be one of the following two types: A diode bridge with series connected DC/DC converter (e. g. a step-up converter) or a controllable rectifier with power electronic switches (see below). The latter type is more expensive and has higher losses but has advantages such as improved regulation and protection. Also, achieving the bidirectional conversion capability needed in wind turbines is much easier using a controllable rectifier. If PWM is used to control a controllable rectifier a rapid response time can be achieved and harmonics in the generator current can be reduced. [14]

There are different types of power electronic switches. The simplest are the thyristors, which can be turned on by a control current signal at any time during the positive half-period of the sinusoidal voltage. GTOs can also be turned off during this half-period. Power transistors are even more controllable and can be switched on and off nearly arbitrarily. The most common power transistor type for use in wind turbines is the IGBT, which combines the properties of MOSFETs and bipolar transistors enabling rapid switching at very low driving power. Switching frequencies well into the kilohertz range can be used and IGBTs are therefore often used when PWM-control is needed. When IGBTs are used as switches a freewheeling diode is connected antiparallel to each IGBT to conduct current in the opposite direction of the IGBT and for its protection. The IGBT is currently the most common power electronic switch type for wind power applications. [14,19]

If the rectifier and DC link are properly chosen and controlled the inverter, being the closest link in the chain to the grid, will be the most important converter part with regard to power quality. As previously mentioned, there are two major types of inverters to choose from: Force-commutated and line-commutated (see Chapter 5.1.3). It follows from the reasoning in the previous passages that force-commutated inverters are the most commonly used today, since they mount PWM-controlled IGBTs and therefore are very much more flexible and controllable than the thyristor switched line-commutated inverters. Also, line-commutated inverters create large amounts of low order integer harmonics, while PWM-controlled force-commutated inverters will produce very little harmonics below their (high) switching frequency. Furthermore, force-commutated inverters can be used for reactive power compensation and, if certain specifications are met, also help in grid frequency stabilization. [13,14,31]

6.2.2. The Fundamentals of Harmonics

As previously mentioned, there are three types of harmonics: Integer harmonics, interharmonics, and subharmonics (see Chapter 3.6.2). In discussions of harmonics the norm is that if no subtype is specified the main focus is on integer harmonics, which is the most common subtype. Interharmonics are less common and also sometimes associated with an integer harmonic and subharmonics are rare. Integer harmonics are usually referred to by their harmonic number (h). This number multiplied with the fundamental frequency equals the frequency of the integer harmonic. Harmonic numbers are used to simplify mathematical treatment of harmonics and to be able to use the same labels independent of the value of the fundamental frequency – which can vary with the area of the world or the application in question. The fundamental frequency is represented by h = 1; h = 0 may refer to a DC offset but this is a less common representation. An example of a waveform comprised of a fundamental frequency component (h = 1) and a 3rd harmonic frequency component (h = 3) can be seen in Figure 24. [1,9]

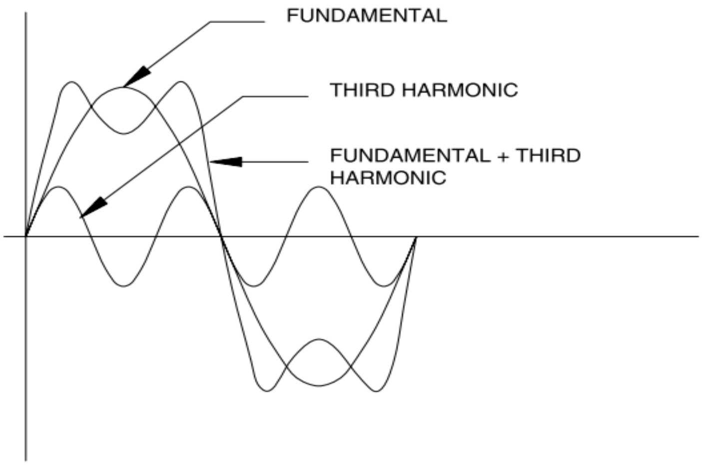

Figure 24. Waveform comprised of a fundamental and a 3rd harmonic frequency component. [1]

The very common further division of integer harmonics into odd (h = 3, 5, 7, 9,…) and even (h = 2, 4, 6, 8,…) is useful since most equipment connected to the power system – including wind turbines – only generate odd integer harmonics. Odd harmonics are created by equipment which draws the same current waveform during both the positive and negative half-periods of the current, which must be the case for e. g. rotating machines to ensure smooth operation. Even integer harmonics can be generated during normal operation of some specific loads under certain conditions, but usually their presence indicates malfunctioning equipment somewhere in the system. Even harmonics are therefore left out of most discussions of harmonics in the power system or are at least given very little room; which will be the case also in this thesis. [1,8,9]

Another previously mentioned and useful division of integer harmonics is division according to which phase sequence is dominant; the positive sequence (h = 1, 4, 7, 10,…), the negative sequence (h = 2, 5, 8, 11,…), or the zero sequence (h = 3, 6, 9, 12,…). The positive sequence harmonics have predominantly the same phase rotation as the fundamental, the negative have the opposite phase rotation and for the zero sequence harmonics all three phases have the same phase angle. The latter group may deserve special attention in some cases because the fact that all three contributions are in phase causes the zero sequence harmonic levels in a potential neutral wire to triple. Since even harmonics are not interesting, however, the odd zero sequence integer harmonics have been given a distinct name to be used when zero sequence harmonics are handled specially: Triplen harmonics (h = 3, 9, 15,…). [1,9]

Interharmonics, in contrast to integer harmonics, are usually transient phenomena or at least not constant over time. Interharmonics can appear as discrete frequencies or as a band spectrum and sometimes appear as sidebands to integer harmonic frequencies. To be able to generally discuss interharmonics they are sometimes grouped with the boundaries between the groups placed at the integer harmonic frequencies. Sometimes interharmonic groups are represented by the frequency in the middle of this interval and by the total RMS value of the interharmonics in the group. For example, the interharmonic group between the 22^{nd} and 23^{rd} integer harmonic would be labeled 22.5 and be represented by a single RMS voltage value. Converter-fed wind turbines can generate interharmonics, especially if the switching frequency of the converter is varied causing harmonics which are integers of the switching frequency to sometimes be integer harmonics and sometimes interharmonics. [1,8,9,13,27]

6.2.3. Quantifying and Measuring Harmonics

Quantifying harmonics is not as difficult as for flicker. Harmonic voltage levels are presented with their relative magnitude (u_h) in percent of the fundamental. The formula for u_h is found in Equation 10, where U_h is the RMS value of the harmonic frequency component and U_1 is the RMS value of the fundamental frequency component. The index "h" in Equation 10 is adapted to the harmonic numbers of integer harmonics, but the same formula can be applied for interharmonics as well using non-integer values for h. The relative magnitude is used for setting limits to individual harmonic frequencies or frequency groups. However, a limit for total harmonic distortion (THD) is also always set (see Equation 11). [2,9,27,29,30]

The THD value is a cumulative measurement of the harmonic distortion caused by all integer harmonic frequencies deemed relevant to measure – interharmonics are not included in the THD. The THD is the most commonly used cumulative measurement for harmonics. It is used primarily for voltage distortion but also for current distortion. When current distortion is researched specifically – for example in wind turbines – the name total harmonic current distortion (THC) value is sometimes used instead of THD; the THC being the exact equivalent for currents of the THD. The THD/THC is a good indicator of increased losses and heat generation due to harmonics, but may sometimes be misleading (e. g. when assessing the increased stress on capacitors caused by harmonics). Therefore, it is important to know the limitations of the THD value when using it to assess if harmonic levels are harmful to the power system or the wind farm itself. Other values than the THC, such as total demand distortion (TDD), might be more suitable to use for current distortion measurements in some cases due to these limitations of the THD. [2,9,27,29,30]

$$u_h = \frac{U_h}{U_1} * 100 \quad (10)$$

$$THD = \sqrt{\sum_{h=2}^{40} u_h^2} \quad (11)$$

Measuring harmonics in wind farms is done following the standards SS-EN 61400-21 [30] and the more general SS-EN 61000-4-7. Here follows a brief description of the procedures detailed in these standards: [30]

When assessing the harmonic distortion from wind turbines measurements of all three phase currents and voltages are performed for different levels of generated active power during a time interval of 10 min. At least three 10 min measurement series per phase current and phase voltage should be performed. The reactive power is kept as low as possible during the tests. For wind farms the tests are usually performed at the PCC. When all measurement data has been collected a discrete Fourier transform (DFT) is applied (without any special weighting functions) to all measured currents to evaluate the frequency content of the current. All harmonics up to the 50th integer harmonic (i. e. up to about 2.5 kHz in Sweden) are regulated by the IEC and should therefore be specified. Transient harmonics – e. g. caused by wind turbine startup or switching between turbines – are permissible to ignore in these measurements because of their low impact on the power system. [9,27,30]

For fluctuating harmonics sources such as wind turbines interharmonics are grouped and labeled according to the principle mentioned above. More specific instructions on how to group interharmonics up to 9 kHz are detailed in SS-EN 61000-4-7. For wind turbines the integer harmonics should also be specified as groups. When harmonic levels for certain frequencies are very low they can be omitted. For this reason the THD measurement in the Swedish Standard only includes integer harmonics up to h = 40 (instead of h = 50; see Equation 11), since higher frequency harmonics are uncommon – and also often transient and hard to measure correctly. Also, there are no specific limits for u_h for integer harmonics above h = 25 in Sweden below the UHV level. Harmonic frequencies over the 25th - 50th integer harmonic – depending on system properties – cause no disturbances to the power system itself and are therefore not as important to mitigate. However, these high frequency harmonics may still affect sensitive loads. [2,9,27,28,29,30]

At present, there are no specified PLs for interharmonics in the Swedish Standard at any voltage level. (There is a TL at the UHV level stating that the total relative magnitude of interharmonics should be below 0.5 %.) This is mostly due to the fact that interharmonics are still relatively poorly understood compared to integer harmonics. This, in turn, is because interharmonics have only recently – due to the ever-increasing number and complexity of power electronic devices and non-linear loads in the power system – increased to levels which sometimes cause them to require special attention. Interharmonics are currently being investigated at many levels and more specific rules are likely to start appearing in the coming years. The fact that there are no rules in the Swedish Standard as of now does not, however, mean that the network owners are not setting demands in this area. Instead it means interharmonics are handled more on a case-by-case basis for installations which are likely to cause interharmonics. [2,9,21,22,27,28,29,30]

The allowed levels, TL and PL for THD and u_h, of integer harmonics presented in the Swedish Standard are the values which 95 % of all the 10 min measurement values (described above) must be below during a week. For the UHV level the TL is THD = 4 % while the PL is THD = 3 %. At the HV level the THD limit is currently under consideration along with some of the u_h limits. The u_h limits for the specific integer harmonics are divided into three categories: Odd non-triplen harmonics, triplen harmonics and even harmonics. The limits are stricter for the two latter categories but the first category is the one causing the most problems. [2,21,22,23,28,29]

The most common harmonic frequencies internationally are the 3^{rd}, 5^{th}, 7^{th} integer harmonics. Some countries have big problems with these low frequency integer harmonics. Wind turbines do not contribute to the emissions of the 3^{rd} harmonic since these emissions are not generated by three-phase converters, only single-phase converters. This is one of the reasons why the two dominant harmonic frequencies in Sweden are the 5^{th} and 7^{th} harmonics – not the 3^{rd}. The TL for the 5^{th} and 7^{th} harmonics at the UHV level are u_h = 2.5 % for both frequencies. The corresponding PL are u_h = 2.0 % for both frequencies. At the HV level the PL are u_h = 5 % and u_h = 4 % for the 5^{th} and 7^{th} harmonics respectively. For u_h limits for other frequencies and voltage levels I refer to SS-EN 50160 [2] and the guidelines of SvK [28,29]. Limits for specific wind farms are usually determined by calculating emission quotas and are therefore dependent on all the factors previously discussed in relation with emission quotas. [2,21,22,23,28,29]

6.2.4. System Response (Resonance Effects)

The system response is a very important factor in relation to harmonics. The system response can be divided into three subcategories: System impedance at different frequencies, capacitor impedance, and resonance effects. The system impedance calculations are done as detailed in the beginning of this Chapter, but for harmonics they need to be done at the different relevant harmonic frequencies as well. Usually a simplification is made here, that the system impedance is a purely inductive reactance. This is a very helpful simplification since the inductive reactance part of the system impedance increases linearly with the frequency and this assumption is also fairly accurate since the power system generally has dominating inductive properties. The simplification allows for the use of Equation 12, where Z_h is the system impedance at the h^{th} harmonic frequency, h is the harmonic number, and Z_1 is the system impedance at the fundamental frequency. The impedance calculations can then be performed only at the fundamental frequency and, using the resulting Z_1, be easily recalculated to all relevant harmonic frequencies with Equation 12. [9,21,22]

The values for the harmonic distortion produced with this simplification will be conservatively high. However, if the results should prove too inaccurate a slightly less conservative approximation could be made: A resistance value could be calculated as well for the fundamental frequency and then be assumed unaffected by the frequency while the reactance is still changed according to Equation 12. This assumption is fairly accurate at least for low order harmonic frequencies (where the most problematic harmonics are usually situated). The presence of shunt capacitors connected to the power system near the wind farm will, however, decrease the accuracy of the above simplifications since the capacitive reactance part of the system impedance decreases, not increases, linearly with increased frequency. For systems with large amounts of capacitance this must be considered in the impedance calculations to arrive at accurate impedance values for harmonic frequencies, which makes the calculations much more complex. [9,21,22]

$$Z_h \approx h * Z_1 \tag{12}$$

Resonance effects between the power system and the wind farm can cause preexisting harmonics on the grid to be amplified. Every grid containing both inductive and capacitive elements has one or several natural frequencies at which resonance will occur. Since the turbines of a wind farm are usually connected radially using cables with predominantly capacitive properties a simplified model of a wind farm connected to a grid can be depicted as in Figure 25. The power system is approximated with a voltage source and an impedance, here assumed inductive, in series. The wind farm is approximated with the capacitance of the cables in parallel with a voltage source with a series inductance representing the wind turbines. If the turbines are most accurately described as voltage or current sources might vary depending on the characteristics of the transformer and converters which in reality are a part of the circuit as well, but here it is assumed that a voltage source is the best approximation. The inductance of the transformer between the wind farm and the PCC is also included in Figure 25. [8,9,23]

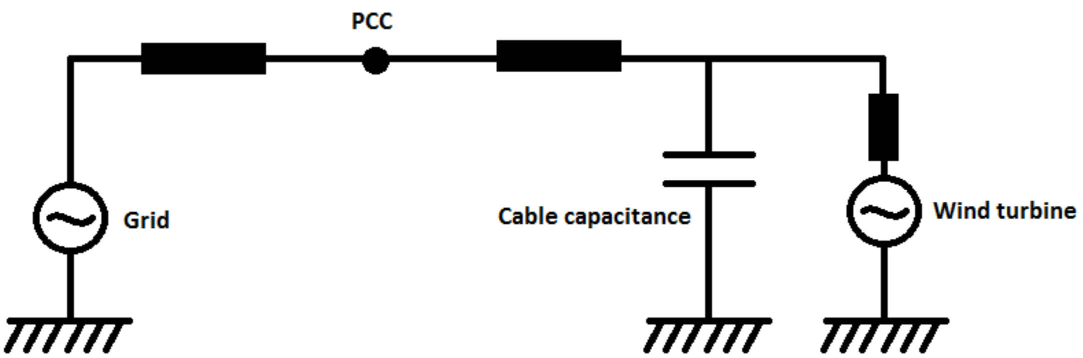

Figure 25. Simplified model of a wind farm connected to a grid.

Since the cable capacitance of the wind farm is usually very dominant for harmonic frequencies the wind turbine leg can be ignored when Figure 25 is viewed from the grid side of the PCC. Seen from this side the model will then have the appearance of a series LC-circuit and series resonance effects can amplify certain harmonics already present on the grid side of the PCC. If, on the other hand, the model in Figure 25 is seen from the wind turbines the cable capacitance appears to be coupled in parallel with the grid inductance creating the appearance of a parallel LC-circuit. This means that the same wind farm can amplify harmonics due to parallel resonance in one part of the grid and at the same time amplify other harmonics in another part of the grid due to series resonance. In a worst case scenario these resonance effects can cause severe harmonic distortion. This occurs when a high level exists of a certain harmonic frequency which precisely corresponds to a natural frequency of a part of the grid. [2,8,9,23]

Network owners usually have limits for how much amplification a specific wind farms is allowed to cause in the power system to prevent severe resonance problems. Since the resonance effects depend on the strength and the natural frequencies of the part of the grid where the wind farm is connected the limits sometimes depend on these factors as well. For example, the Swedish Standard motivates its lack of specific limits to interharmonics at the HV level with the fact that the resonance frequencies of the grid at this voltage level are generally too low for interharmonics to be a problem, since interharmonics are usually only problematic when amplified through resonance. Resonance effects are generally mostly a problem at low order harmonic frequencies. [2,21,22,23]

Harmonics can appear to be a big problem simply because the power system is largely designed considering only the fundamental frequency and therefore handling harmonics may require different measurements and mitigation techniques than classic power system issues, such as for example reactive power compensation. Handling interharmonics is especially difficult because they are rarely constant and, since they are not multiples of the fundamental frequency, one period of the fundamental frequency is no longer enough to describe the waveform (as it is for integer harmonics). In reality, however, harmonic distortion is seldom a problem in Sweden. Most often the emissions stay within the allowed limits. [9,22]

6.2.5. Mitigation of Harmonics in Wind Farms

To summarize the previous subchapters, when harmonic distortion at a wind farm reaches levels that require mitigation this is usually a result of either too high emissions from the turbines' converters or of the wind farm amplifying preexisting harmonics in the power system too much. There are three basic principles for handling this problem: Reducing the harmonics generated by the wind farm, suppressing the harmonics using mitigation devices (passive filters), and modifying the frequency response of the power system. [9]

Reduction of the harmonics generated by the wind farm is mostly a solution when excessive emissions are predicted already in the planning phase of the wind farm project. This is seldom an economically or practically viable solution when the wind farm is already constructed since it may involve alternative choices of equipment (e. g. converters), location, or structure of the wind farm. Changing the characteristics of the converters, to a degree, is often possible through software updates or slight modifications to the hardware, but this is also more easily done during the construction of the wind farm instead of after its completion. One reason for this is that if secondary problems should arise as a consequence of such modifications the conditions for mitigating these are much better before or during construction than after. [9,21]

When designing a wind farm it is therefore important to consider harmonic disturbances early in the process. In the early stages you probably already have to deal with harmonics causing problems internally in the wind turbines, to assure smooth operation without tower oscillations etc. These kind of internal design issues of the wind farm (not pertinent to the power quality of the grid) might also require the constructor to consider high frequency harmonics; even higher perhaps than the 50^{th} integer harmonic, which as previously mentioned is the highest order harmonic regulated by the IEC. At this stage you also have to consider the wind farm's withstand strength to power quality disturbances. This is done both to guarantee smooth operation and because this too is regulated in the Swedish Standard. [9,21]

Modification of the system frequency response can be done by adding shunt filters, which will be discussed further in coming paragraphs, to suppress the preexisting harmonics. Also, adding reactors in shunt or in series will change the natural frequencies of the system and can alleviate resonance effects. Furthermore, capacitors can be installed or existing ones can be modified or moved to produce a changed system response. [9]

The use of passive filters is the overwhelmingly most common method for mitigating harmonics in wind farms, both externally and internally. Passive filters meant for harmonics mitigation have mainly inductive and capacitive properties, and can therefore double as reactive power compensators. Since the reactance of inductors (X_L) increases with increasing frequency while the reactance of capacitors (X_C) decreases with increasing frequency very simple filter designs can provide a response tuned to filter out specific harmonic frequencies. As previously mentioned there are three basic types: Shunt filters are the most common, and then there are also series filters and low-pass filters. Shunt filters work by providing a low-impedance path to ground for the targeted harmonic frequencies while the fundamental frequency component passes by undiverted. Shunt filters are preferably used for voltage harmonics mitigation since their main component is the capacitor, which is a component that resists fast changes in voltage. Passive series filters work instead by providing a high-impedance path for the harmonics and thereby blocking those while allowing the fundamental to pass through the filter unhindered. Passive filters are used primarily for current harmonics mitigation, since their main component is the inductor which resists fast changes in current. A shunt and a series passive filter in their most basic form can be found in Figure 26 a) and b) respectively. [21,22,23,32,33]

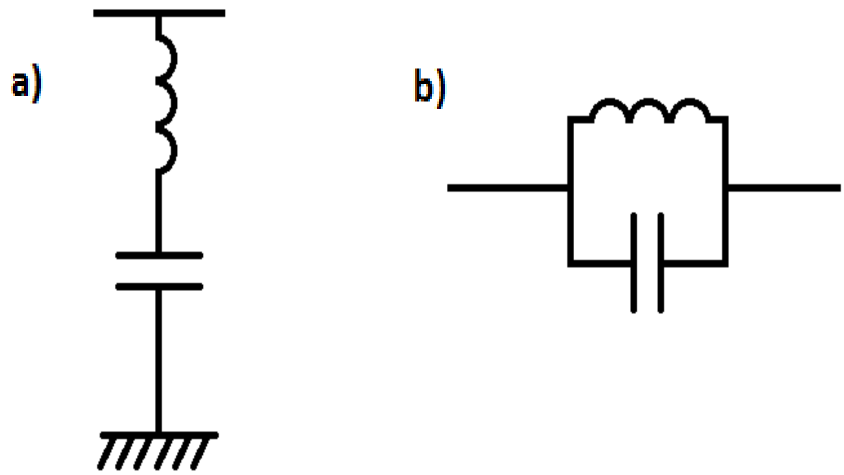

Figure 26. a) Basic shunt passive filter. b) Basic series passive filter.

Passive shunt filters can be further divided into single-tuned, double-tuned and high-pass filters. The subtypes being described below are all single-phase variants but it is also possible to have three-phase filters with for example delta-connected capacitors to provide somewhat different characteristics. For passive shunt filters to be installed the power system must be carefully tuned to avoid natural frequencies near the expected parallel resonance frequencies of the filters. Also, the filters should be installed only at buses where the short-circuit reactance of the system is expected to remain constant. This to avoid the natural grid frequencies changing to values closer than expected to the parallel resonance frequencies of the filters. But, the filters are more effective the closer they are to the equipment emitting harmonics so an assessment must be made where best to place them. For wind farms you must also consider the intermittent nature of the power production and the consequences this will have on the harmonic emissions and the resonance effects. [5,6,9,23]

Single-tuned filters, also be called notch, single frequency, or single branch filters, is the most common subtype of shunt filters. Figure 25 a) depicts an ideal single-tuned filter. In reality the resistance of primarily the inductor has to be taken into consideration. This internal resistance of the inductor, and also to a smaller degree of the capacitor, is usually depicted as a series resistor. The total impedance of the single-tuned filter can then be described with the formula in Equation 13. The resonant frequency (f_0), i. e. the targeted frequency where the filter's impedance is lowest, is obtained through Equation 14. Since the resistance present in the filter is a deviation from the ideal single-tuned filter characteristics there is a quality factor (Q) for single-tuned filters dependent on this resistance (see Equation 15). A high Q value indicates lower losses and sharper tuning and corresponds to a low resistance value. At the resonant frequency the inductive and capacitive reactance values are equal and the filter impedance consequently purely resistive (see Equation 13). This makes the inductive and capacitive reactances interchangeable in the formula for Q. [6,9,32]

$$Z = R + j * (X_L - X_C) = R + j * \left(2\pi f L - \frac{1}{2\pi f C}\right) \tag{13}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{14}$$

$$Q = \frac{X_L(f_0)}{R} = \frac{X_C(f_0)}{R} \tag{15}$$

Single-tuned filters create a parallel resonance frequency below the resonant frequency f_0. This parallel resonance frequency must not coincide with a natural frequency of the system or a harmonic frequency with high emissions. Therefore, single-tuned filters are usually tuned to a slightly lower frequency than the targeted harmonic frequency to create a safety margin against changes in the impedances of the system or filter, e. g. due to temperature changes or faults. Such changes can otherwise cause the parallel resonance frequency to drift too close to the targeted harmonic frequency. If this happens, much worse harmonic distortion could ensue than if the filter had been omitted. For example a single-tuned filter for the 7^{th} harmonic usually has a parallel resonance frequency close to the 5^{th} harmonic, which means a 5^{th} harmonic filter is usually needed whenever a 7^{th} harmonic filter is installed to counter the effects of this parallel resonance even if the 5^{th} harmonic was not originally a problem. [5,6,9]

Double-tuned filters are designed to replace two single-tuned filters. They have two resonant frequencies where the filter impedance is low. An advantage compared to using two single-tuned filters is more efficient use of the components (especially the capacitors), but double-tuned filters are economical only in large sizes. A typical double-tuned filter is shown in Figure 27. [9,33]

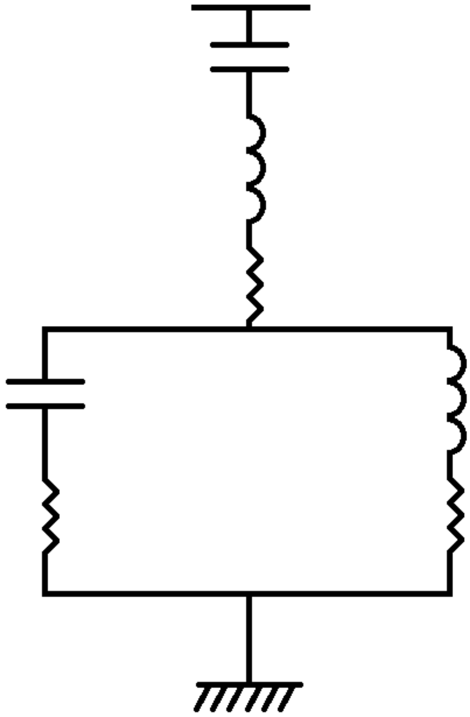

Figure 27. Double-tuned passive shunt filter.

High-pass shunt filters are designed to divert a whole range of harmonic frequencies to ground, making them the most suitable filter type for interharmonics mitigation. All frequencies above a certain frequency called the corner frequency or the cut-off frequency are attenuated. A high-pass filter which is to replace single-tuned filters must consequently have a cut-off frequency lower than the lowest order harmonic causing problems. The different variations of high-pass filters are usually classified through the highest order exponent present in the denominator of their transfer functions. A 1^{st}, a 2^{nd}, and a 3^{rd} order high-pass filter are depicted in Figure 28 a), b), and c) respectively. The filters in Figure 28 are just examples of high-pass filters of these first three orders; many variations and also higher order high-pass filters exist. The losses at the fundamental frequency decrease with increasing filter order while high order high-pass filters tend to become less efficient at filtering. The resistances provide a dampening effect which can be used to control resonance phenomena but causes higher losses and decreased efficiency, especially at high frequencies. [5,9,32]

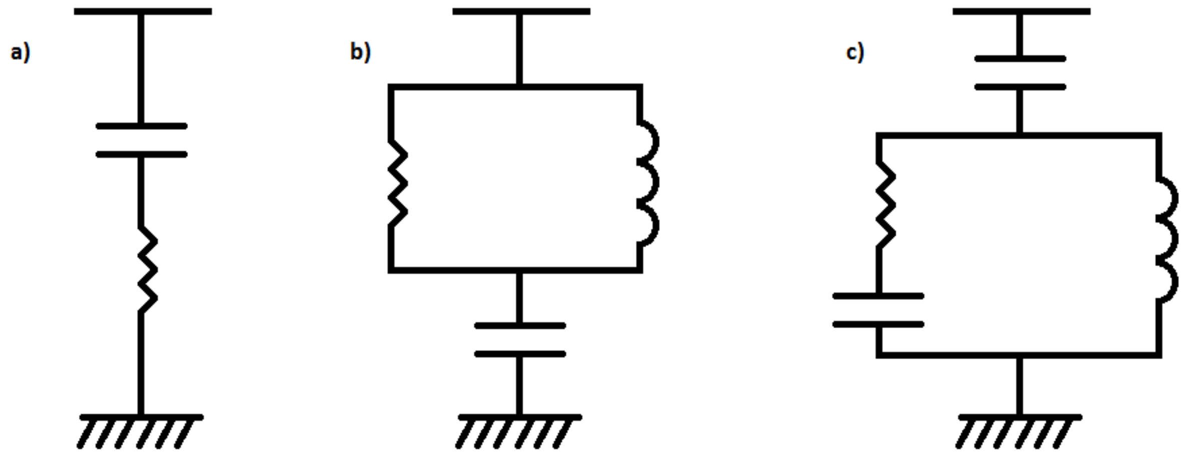

Figure 28. a) 1st order high-pass filter. b) 2nd order high-pass filter. c) 3rd order high-pass filter.

Completely replacing single-tuned filters with a high-pass filter is not very common. High-pass filters which have a low enough cut-off frequency and can attenuate harmonics to the degree required to completely replace single-tuned filters generally have too high losses associated with them to be economically viable. Instead, a high-pass filter with a higher cut-off frequency is usually connected in parallel with a chain of parallel coupled single-tuned filters. The single-tuned filters are tuned to target the most problematic of the low order harmonics (e. g. 5^{th},7^{th}, and 11^{th}) and the high-pass filter attenuates the higher order harmonics (e. g. caused by converters with high switching frequencies). This setup is called a composite shunt filter and can provide a complete protection against harmonics at a bus. However, when installing composite filters it is important to know there are only low levels of even harmonics present since parallel resonance frequencies will form between the adjacent single-tuned filters. These parallel resonance frequencies often coincide with even harmonic frequencies, for example the resonance frequency between the filters for the 5^{th} and 7^{th} harmonic will often coincide with the 6^{th} harmonic frequency. However, as previously mentioned even harmonics are rare in the power system. [5,32]

Passive series filter most often look very much like in Figure 26 b), comprised of a capacitor and an inductor in parallel placed in series with the line. Passive series filters are less common than shunt filters due to the fact that they are placed in series with the main supply line and therefore have to handle the entire line current, while shunt filters only handle a fraction of the line current. Also, the series filters must be able to withstand all occurring over currents. The consequence is that a series filter must be larger and more robust than a shunt filter to perform more or less the same function (although aimed more at current harmonics than voltage harmonics, as previously mentioned). Limiting the resistance of the inductor (and less crucially that of the capacitor) to reduce losses becomes of greater importance for series filters and thereby the real series filter more closely resembles the ideal circuit in Figure 26 b). But, usually a series filter still has higher losses than a corresponding shunt filter. [6,9]

A series filter is tuned to a specific frequency by means of carefully choosing the capacitance and inductance values of the components; the same way as for the single-tuned shunt filters. The values are chosen to provide as little impedance as possible at the power frequency but a very high impedance at the targeted harmonic frequency. When multiple series filters are used to provide a more complete protection they are placed in series with each other (not in parallel). Series filters also lack an equivalent to the high-pass shunt filter, making them expensive to use when many different harmonic frequencies needs attenuation. Therefore, series filters are seldom used exclusively, but in combination with various shunt filters. However, since series filters are placed in series with line they could be used to change the system response, which might in some cases make a series filter useful for other reasons than mitigation of its targeted harmonic frequency. [6,9]

Low-pass filters are an alternative to high-pass shunt filters for filtering out a whole range of harmonic frequencies. A low-pass filter in its most basic form, comprised of an inductor in series with the line followed by a shunt capacitor, is seen in Figure 29. Low-pass filters, just like high-pass shunt filters, have a cut-off frequency and attenuate all frequencies above it. The fundamental frequency component passes through the inductor and past the capacitor unhindered. More complex low-pass filters with for example capacitors on both sides of the inductor (creating a pi-circuit) can also be used. Also, the working principle of a low-pass filter can be used as follows: A capacitor bank is installed on the low-voltage side of a power system transformer and dimensioned to provide a suitable cut-off frequency together with the transformer's leakage inductance and the grid inductance. This setup will hinder harmonics from the low-voltage side reaching the high-voltage side. For wind farms, this would mean that harmonics caused by the wind farm can be kept from entering the power system by installing a capacitor bank just before the main transformer at the PCC. The cut-off frequency of a low-pass filter can be placed low enough not to risk causing any unwanted resonance. If the cut-off frequency is placed well below the 3rd harmonic frequency there are no significant harmonic frequencies below the cut-off frequency that can be amplified by its parallel resonance frequency. [9]

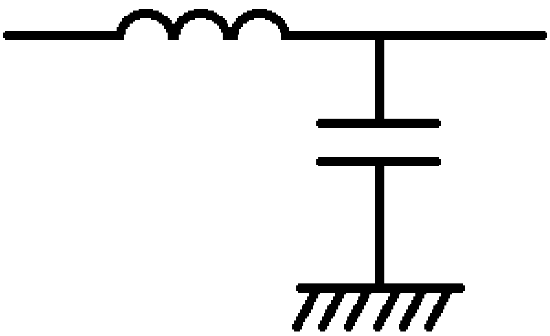

Figure 29. Basic low-pass filter.

When dimensioning shunt filters the capacity of the bus must be considered as well as the characteristics and emissions of the harmonics source. The magnitude of the currents the filter might have to withstand during both continuous operation and faults must be considered for all filters, but as previously mentioned this is a more critical design issue for series filters. Even though passive filters have low maintenance requirements they do become less efficient with age; like all power system components. Primarily, filter detuning is a problem. This can be caused by for example capacitor ageing and is mitigated through normal maintenance (in extreme cases retuning the filter or lowering the quality factor could be considered). [6,9,23]

Here follows a general procedure for passive filter design, primarily focused on single-tuned shunt filters. When designing composite filters comprised of multiple passive filters of different types and orders the interaction between them must also be evaluated. Sometimes, in order to alleviate problems discovered in the evaluation process, the quality factor can be altered by adding resistance to introduce damping of the system response: [9]

1. **Select a frequency to tune the filter to**. The selection is done based on calculations or measurements of harmonic emissions from the harmonics source (wind farm) or expected amplification due to resonance. The filter is tuned to a frequency slightly below the targeted harmonic frequency.
2. **Compute capacitor size and the resonant frequency**. When dimensioning the capacitor the reactive power injection it causes must be considered. The capacitor can be chosen to provide reactive power compensation as well as harmonics mitigation. The withstand voltage of the capacitor must be high enough to allow a voltage rise across the reactor, which may sometimes require it to be higher than the withstand voltage of the bus.
3. **Compute reactor size** using the computed resonant frequency and capacitance (see Equation 14).
4. **Evaluate filter duty requirements** such as peak voltage and current, reactive power production, and RMS voltage according to the relevant IEC Standards.
5. **Evaluate filter frequency response** to make sure new parallel resonance frequencies do not cause problems.
6. **Evaluate the effects of filter parameter variations within specified tolerance intervals**. There are always intervals of allowed deviations from the nominal value for e. g. capacitance and inductance. Variations within these specified limits can sometimes cause a significantly changed performance of the filter. [9]

The main advantage of passive filters, which makes them the dominant mitigation devices for harmonics, is their simple, robust, and cheap design. Also, passive filters can be constructed in large sizes (power ratings) and require minimal maintenance. Furthermore, they can double as reactive power compensators and do not contribute to short-circuit currents. Disadvantages include their tendency to cause resonance problems if not carefully tuned to match the power system. Other noteworthy limitations include their dependence on the power system impedance and their inability to adapt to changes in harmonic content, e. g. due to different operational modes of wind farms, changes in temperature, and faults. Once installed, changing the tuning of a passive filter is not very easily done. Their large size can also be a disadvantage under certain circumstances. [5,6,9,21,22,23,24]

Generally, the lack of flexibility is a major weakness of passive filters. Increased flexibility is the main reason for using active components to change filter parameters or for using active mitigation devices based on power electronics (some of which are described in Chapter 4).

However, since excessive levels of harmonics very rarely occur in the Swedish power system today, passive filters are almost always considered enough. Even in cases where the harmonic content is varying and interharmonics occur (providing unfavorable circumstances for passive filters), the distortion level is never high enough to warrant active mitigation devices. In fact, none of the representatives of companies in the Swedish power system industry interviewed for this thesis have ever encountered an active mitigation method being used. As previously mentioned, though, in internal mitigation of harmonics passive filters are built into (and attached to sockets on, if more filters are required) the converters of the turbines and their parameters are made changeable through power electronics because mass production of wind turbines for sale in many different markets requires a level of flexibility that passive filters otherwise lack. [5,6,9,21,22,23,24]

Besides filter selection, an important factor when designing a wind farm with respect to power quality mitigation is to choose transformers able to block triplen harmonics; if such harmonics are a problem. This can be done by using isolated delta-wye or zigzag transformers (see Chapters 4.3.2 and 4.3.1 respectively) to trap zero-sequence harmonics on one side of the transformer. The characteristics of transformers can affect the levels of other harmonics as well (as mentioned when low-pass filters were discussed). Also, using equipment with higher withstand strengths to harmonics throughout the power system is a measure which could potentially greatly reduce power quality problems. A significantly contributing factor to the increasing problems with harmonics is the ever-increasing number of sensitive loads connected to the grid. Stricter rules for what disturbance levels end-user equipment as well as power system equipment must be able to handle would lessen the need for harmonics mitigation. As previously mentioned, stricter Swedish rules for withstand strength in power system equipment are already underway. [21]

Harmonics mitigation is not just performed because it is required by the Swedish Standard, it has economic advantages as well as. Better power quality can lead to energy savings if the mitigation methods chosen have lower associated losses than the power quality disturbances they mitigate would have caused without mitigation. This is especially relevant for harmonics since they are the dominate disturbance type and also because harmonics are steady-state disturbances and therefore cause much higher losses than transient phenomena. Reducing harmonics also increases the life span of equipment by slowing down their ageing process. Furthermore, producing high quality power might also help provide a competitive advantage. These might be considered reasons to aim for higher power quality in new wind farms than required by the Swedish Standard and the network owners, primarily through more efficient harmonics mitigation. [32]

6.3.Other Power Quality Disturbances in Wind Farms

The following power quality disturbance types have to be considered in different ways when designing wind farms, but are not as serious problems as flicker and harmonics. The few power quality disturbance types described in Chapter 3 that are not included here are either very rare or not relevant with respect to large wind farms and the areas of the grid where they are connected. [21,22,23]

6.3.1. Unbalance in Wind Farms

Current and voltage unbalance is, as previously mentioned, a state where the current and/or voltage of the three phases have different magnitudes at a bus or where the phase angle between adjacent phases deviates from 120^o. This can be caused by poorly constructed wind farms, where the connections between the turbines are not properly placed and dimensioned. Also, the location of the wind farm, or rather the location of its PCC, must be considered. Connecting a wind farm in the middle of a transposed transmission line can create unbalance issues, since the transmission lines are only designed to provide balanced voltages at their end points. There have also been cases where improper converter operation has caused some levels of unbalance, but this is unusual. [6,21,23]

In the Swedish power system unbalance is not mitigated, it is prevented. Through a properly thought-out design of the power system, the wind farm, and the connection between them unbalance can be eliminated. As previously mentioned there are some active mitigation devices, such as SVCs or SSCs, which used in suitable configurations and with special control systems can handle unbalance (see Chapter 4.6). These devices are, however, too expensive and complicated to be under consideration in the Swedish power system since problems with unbalance are extremely rare. [6,8,21,22,23]

When measuring unbalance positive and negative sequence components (see Chapter 3.6.2.1) of the voltage/current are measured; zero sequence components are usually ignored since most often only low levels exist. Then the ratio between the negative sequence components created during unbalanced conditions and the positive sequence components is calculated. There are a couple of variations of the same basic procedure for quantification of unbalance based on this ratio. The IEEE requires calculation of an unbalance factor while the IEC Standard SS-EN 61000-4-30, which is followed in the Swedish power system, just uses the previously calculated ratio expressed in percent. The ratio should be based on at least a week's worth of 10 min measurement series and the values that are not exceeded 95 %, 99 % and 100 % of the time should be presented. [2,6,8,28,29]

The TL at the UHV level is a ratio of 1 % or less for the 95 % value and the corresponding PL is 1 % for the 99 % value. For the HV level the PL is generally 2 % for the 95 % value in the Swedish Standard, but exceptions are allowed under special circumstances. At the HV level and below it is not uncommon that network owners have stricter limits than the Swedish Standard. Also, depending on the network owner, the limits for specific wind farms might be set using emission quotas. [2,22,23,28,29]

6.3.2. Long-Duration Voltage Variations (Rapid Voltage Changes) in Wind Farms

Wind farms must be able to withstand the long-duration voltage variations allowed by the Swedish Standard. There are no limits for interruptions since they are very unpredictable. The aim is just to minimize their occurrence, but wind farms must of course still be able to withstand them. No general TL or PL values exist for over- and undervoltages at the HV and UHV levels. At these high voltage levels limits are set individually for each part of the power system and individual contracts written for all producers and consumers that detail these limits. At lower voltage levels the Standard allows variations of ±10 % of the RMS voltage, but as previously mentioned the limits set by the network owners are often stricter. [2,28,29]

The number of planned occurrences of rapid voltage changes is regulated by the Swedish Energy Markets Inspectorate (sv: Energimarknadsinspektionen). There are two percentages used to define which rapid voltage changes are limited: The relative change in RMS voltage before and after the rapid voltage change (ΔU_{stat}; i. e. the steady state voltage change) and the maximum relative change during the rapid voltage change (ΔU_{max}). For $\Delta U_{stat} \geq 3$ % or $\Delta U_{max} \geq 5$ % a maximum number of 12 rapid voltage changes are allowed per 24 h period for reference voltages equal to or above 45 kV (24 changes are allowed below 45 kV). This is widely considered too generous by Swedish network owners and therefore they usually set much stricter limits. For example, the TL and PL at the UHV level (set by SvK) are the same and allow no rapid voltage changes at all with $\Delta U_{max} > 5$ %, two changes per year when 4 % < ΔU_{max} < 5 % (but exceptions can be made), and four changes per 24 h period when 2 % < ΔU_{max} < 4 %. When ΔU_{max} < 2 % rapid voltage changes are treated as flicker. [7,22,28,29]

The effects of rapid voltage changes, just likes those of flicker, are subjective unless the disturbance is really severe. One study shows changes with $\Delta U_{max} > 1.5$ % are visible to a majority of people exposed and changes with $\Delta U_{max} > 4$ % are visible to 95 % of people when the change is instantaneous. The perceptibility becomes lower for slower changes. In general, changes with $\Delta U_{max} > 2$ % are considered able to produce noticeable lighting changes in incandescent light sources. [8]

Wind farms can cause rapid voltage changes primarily when turbines are switched on or off. Since changes with $\Delta U_{max} > 5$ % are not tolerated, at least by some network owners, a wind farm should be dimensioned so that the maximum possible ΔU_{max} of a rapid voltage change caused by the wind farm – which occurs when a start at rated wind speed or a complete shutdown is performed – is less than that. Complete shutdown is only performed when the wind speed is dangerously above the rated wind speed. This, just like a start at rated wind speed, occurs very rarely at most locations; once every year or every few years generally. This seldom a change with $\Delta U_{max} > 5$ % might be tolerable and the focus can be shifted to minimizing the change when starting single turbines. Here, the use of soft starters (see Chapter 6.3.3) or other methods of limiting the turbine's energizing current at startup is vital for avoiding large rapid voltage changes or even voltage dips. If this is not enough to arrive within the allowed limits the operation of the wind farm must be altered to require fewer turbine switching events. [8]

6.3.3. Voltage Dips in Wind Farms

Voltage dips in wind farms are unpredictable and occur relatively seldom. They are caused by switching actions – primarily startup of turbines – and are not mitigated but instead eliminated through soft start of the turbine generators. The different methods that exist for soft start of generators all aim at reducing the high inrush currents at startup that arise because the generator core requires magnetization. A direct-start of the generator with the associated drastic increase in drawn current may be more efficient when only considering the generator itself, since a direct-start is faster. However, a direct-start will cause variations in the voltage such as rapid voltage changes or, worse, voltage dips, as well as torque shocks. [2,14,27]

The simplest method of soft starting a generator is the wye-delta connection. The generator core must be designed especially for wye-delta start and the method does not work as effectively for turbines without pitch-control (see Chapter 5), which, however, is the most common speed-control system. Wye-delta start is performed as follows: The generator is wye-connected at the beginning of the startup procedure. This reduces the initial current with a factor $\sqrt{3}$ and the drawn power by a factor 3. When the inrush current peak has passed the generator is then reconnected as delta. [14,19]

Another starting technique utilizes a so called soft starter. This method utilizes a pair of antiparallel thyristors per phase and continuously alters the firing angle of these thyristors during startup to achieve a gradual increase in voltage and current. The current can hereby be limited to nominal operating values. Soft starter operation produces transient harmonics, but these generally do not cause any problems since they have very short durations. [14,34]

The over mentioned methods for soft start are mostly pertinent to induction machines. However, when using direct-driven synchronous generators a synchronization device is always used to be able to connect the generator to the grid and this device also ensures smooth startup without voltage dips. [14,19]

Using these soft starting methods voltage dips caused by wind farms can be eliminated. The wind farms will then not have any negative effects on the number of voltage dips. Voltage dips will then only need to be considered with respect to the wind farms' withstand strengths. Indirectly, however, wind farms can help to reduce the number of voltage dips, since voltage dips become more severe in weak grids and an increased number of wind farms strengthens the grid. (If wind farms replace other less intermittent production facilities the result can be a weaker grid.) Also, wind farms outfitted with SVCs or STATCOMs can be used to improve the ride-through capability of the grid for voltage dip. A current is injected from the mitigation device during the dip to compensate for the discrepancy between nominal voltage and the dip voltage. This method works best if the dip does not originate near the wind farm, but upstream from it, since the source impedance of a shunt device becomes very low for dips generated by faults close to the device. Since the injected current is equal to the injected voltage divided by the source impedance, an effective ride-through for faults close to the device would require a very high current. [8,21,22,23,24,35]

There are no limits for voltage dips in the Swedish Standard due to their unpredictability. Voltage dips are also quite rare in Sweden. Sometimes voltage dips are included in the limits for number of allowed rapid voltage changes (see Chapter 6.3.2) and each dip is then counted as two changes. At the UHV level there are only some tens of voltage dips every year and most of them have only marginally larger relative magnitude than 10 %. In the IEC Standard SS-EN 61000-4-30 there are detailed instructions on how to conduct measurements of voltage dips. Because they are so rare the measurement period is recommended to be no less than a year long, but even that is often too short a time interval to produce reliable statistical data regarding the occurrences of voltage dips. [2,7,27,28,29]

6.3.4. Transients in Wind Farms

Impulsive and oscillatory transients, just like voltage dips and interruptions, are unpredictable events and therefore hard to set applicable limits for. Also, there are no standardized measurement procedures for transients to date, even though some help in setting up measurements is offered in the standard SS-EN 61000-4-30. Fixed-speed wind turbines have sometimes been known to cause oscillatory transients when their capacitor banks are switched. As for voltage dips, however, oscillatory transients can be eliminated by the use of soft starting equipment in wind farms. Impulsive transients are almost exclusively caused by lightning strikes. [2,13,28,29]

Though wind farms do not usually cause transients they must still be able to withstand them. The aim in transients mitigation in the Swedish power system is to minimize the occurrence of transients. Because of their unpredictable nature, however, the main focus of transients mitigation is on insulation coordination. Insulation coordination basically consists of coordinating the maximum amplitude of the transient that is allowed to reach sensitive power system equipment with the withstand strength of the insulation of this equipment. The amplitude of the transients is limited using surge arresters, usually MOVs (see Chapter 4.2.1). These usually need to be placed at incoming lines to power stations and at transformers to protect them. [9,13,21,22,23,33]

Because transformers and substation usually require transients mitigation, there will probably be at least one surge arrester on the grid side of the PCC for a large wind farm. When selecting the main transformer of the wind farm insulation coordination must therefore be considered. Much could be said about transients mitigation. However, since insulation coordination is a general principle of the entire power system and wind farms, as previously mentioned, do not cause transients this will not be discussed further in this thesis. For further details about insulation coordination, measurement of transients and surge arresters I refer to [36]. [36]

6.3.5. Frequency Variations in Wind Farms

There are very strict limits to how much the frequency of the fundamental component of the voltage and current in the Swedish power system is allowed to vary. The nominal grid frequency in Sweden is 50 Hz. On the main grid the maximum deviation allowed by the Swedish Standard during 99.5 % of the year is ±1 % (i. e. 49.5 Hz to 50.5 Hz). The absolute maximum allowed deviation from the nominal frequency is +4 %/-6 % (i. e. 47 Hz to 52 Hz). At the UHV level the value of the power frequency is coordinated between the Nordic countries and the responsibility of regulating the power frequency rests almost exclusively on the network owners in Sweden; particularly SvK. [2,28,29]

As previously mentioned, deviations are caused by a discrepancy between generation and consumption in the power system. Since wind farms produce intermittent power their generation varies constantly, even if the smaller changes are balanced by the converters in new wind farms. This means that wind farms have the potential to cause power frequency variations. Usually, though, – and almost always in the Swedish power system – the generation variations caused by wind farms are balanced by other, more easily regulated power sources such as hydro power plants. A strong grid also helps prevent frequency variations due to the varied power generation of the wind farms. Therefore, power frequency variations are not a problem in the Swedish power system. [13,21,22,23]

7. Computer-Based Tool for Mitigation Method Selection

This thesis project included the investigation into if designing a computer-based tool to aid WSP in choosing appropriate power quality mitigation devices for specific wind farms under planning or construction would be useful. The intent was designing a tool which could be easily used by all WSP personnel involved in the planning phase of a wind farm project. The tool would make the decision of which direction to take regarding the power quality disturbance mitigation easier; a general suggestion of which technology to use for mitigation would be provided, not a detailed analysis or recommendation of a specific mitigation device model.

However, during the course of this thesis project it became apparent that the proposed kind of computer-based tool has no useful application, for reasons which are explained below. Therefore, the decision was made between the author of this thesis and WSP for no computer-based tool to be designed. Before describing why this decision was made the envisioned concept of the tool will now be described in more detail to then be able to explain why this concept has limited practical applications.

The original idea for the computer-based tool was to firstly choose a set of input parameters describing the wind farm project in question and the priorities of its owner pertinent to disturbance mitigation. Examples of what the wind farm specific parameters might have been are rated power of individual turbines and the entire wind farm, connection voltage, location of the PCC, turbine type, and converter type. The priorities of the owner could have been mapped by ranking certain properties of the mitigation devices according to their importance to the owner. Such device properties might have been cost, size, maintenance requirements, expected life span, flexibility, power losses and of course mitigation efficiency.

The second step after identifying the input parameters would have been selecting which mitigation devices to include for the tool to choose between. This selection would have been based on parameters such as the devices' compatibility with the Swedish power system, to what extent they are available for purchase and are accepted solutions in the Swedish power system industry, the future prospects of the technology involved (if the device is being phased out, has a stable position on the market, is brand new and largely untested etc.), and if the price is within reasonable limits for wind power applications. The devices would have been chosen from the list of devices reviewed in Chapter 4; or from variations of those technologies depending on what was available.

Thirdly, the chosen devices would have had to be ranked from best to worst with respect to each of the different parameters and priorities from step one. Some examples of how this process could have been initiated follows: The parameters for PCC location and connection voltage (and possibly other parameters) would be linked to the allowed emission levels for the wind farm and thereby help determine the required attenuation level of the mitigation devices for a certain location. The power rating of the turbines and the entire wind farm would determine the required power rating of the mitigation devices. The turbine type and converter type would help determine which disturbances would require mitigation and that in turn would determine what mitigation devices would be most suitable. When connections like the ones above had been made a table with device rankings for each parameter could have been completed.

The fourth step would have been programming algorithms to link a certain combination of the parameters from the first step to the most appropriate of the mitigation devices chosen in step two for a particular wind farm owned by a particular company. The rankings for the different parameters for each device would have had to be weighted somehow to produce a new ranking with regard to a specific wind farm project. The intent was to do this in Microsoft Excel 2010 to provide a familiar context for the intended users, facilitate integration of the tool into potential preexisting documentation, and ensure compatibility with possible preexisting tools for other parts of the planning process.

Lastly, the user interface would have been constructed to provide ease-of-use for all WSP personnel; with or without expertise in electric power engineering and power quality mitigation. The tool would provide one or several suggestions for mitigation method and also provide a motivation for each suggestion based on the input parameters as well as a simple description of the mitigation devices selected.

The above structure seemed to be the best, maybe the only, way of accomplishing an easy-to-use computer-based tool for disturbance mitigation method selection under the anticipated circumstances. There are, however, several factors which make this kind of tool unusable in practice. The division into internal and external mitigation gives rise to a big problem. The division is not a problem in itself – whether to apply the mitigation internally or externally would just have had to be another input parameter in the tool. The problem with this division lies in the fact that most of the mitigation is done using internal mitigation devices, which means that the turbine manufacturers are in full control of most of the mitigation and whether information about it is available or not. [24]

Because of secrecy policies regarding the technical design of the turbine in general and the converter in particular the turbine manufacturers do not release details about how their internal mitigation works. This means there are very limited possibilities of choosing internal mitigation devices. The choice would instead be between finished turbine models and have to be based solely on the information provided by the turbine manufacturer about the mitigation capabilities of these turbine models. While this might be an efficient and in many ways preferable way of handling the mitigation it is not compatible with the proposed structure of the tool. If the tool was redesigned to adjust for this incompatibility the result would simply be a product catalog of the currently available turbine models without any significant additional information compared to the product catalogs supplied by the turbine manufacturers themselves. [24]

The conformity of the mitigation methods to exclusively include passive filters is another factor which makes the tool impractical. This conformity applies equally to the internal and external mitigation. This means that creating a tool which chooses between devices selected according to step two above would result in it simply choosing between different types of passive filters. This could of course be done but does not seem relevant for the intended area of use (see above) or at all for use in the early planning stages of a project. Choosing filter types, it seems, is more appropriate when all disturbance emission calculations have been performed and then the choice should be based mostly on the results of those calculations, not on parameters such as those in step one above. The choice between filter types seems too technical and too detailed to be made easier by the use of a tool with the proposed structure. [21,22,23]

Only when the pre-installed internal mitigation devices of the turbines are not sufficient is there anything to decide other than how to adjust the filters in the converters. However, only in a fraction of new wind farms does this happen and often the problem can still be solved internally by adding more filters in sockets on the converters, even though external mitigation can be used if specifically requested. A conclusion was drawn from the information presented in this chapter of the report about how mitigation is handled: A tool for mitigation method selection is neither needed nor practical. Therefore, no such tool has been designed. [24]

8. The Future of Power Quality Disturbance Mitigation

This chapter of the report tries to paint a picture of what could happen to the field of power quality mitigation in the future. A few examples of important areas of development and promising technologies are presented and briefly explained. The chapter is divided into three parts: The first part deals with an already existing alternative mitigation approach and then there are two subchapters about the possible future development of wind power and of the power system respectively that might affect disturbance mitigation.

The power system industry is an industry that has well-founded reasons for being conservative. The time-spans which must be considered in this industry when making investments are in many cases several decades. The network owners, and other parties in the power system with wide responsibilities, therefore have to be cautious in their assessments of new technologies to not risk compromising the long-term stability of the grid. However, in some technical areas the power system is under constant change. The ever-increasing number and complexity of the loads being connected to the power system places new demands on an industry that is otherwise used to being able to be conservative. [8,22,23,24]

There are other ways of handling power quality disturbance mitigation than the approach used in the Swedish power system. In some other European countries, e. g. Spain and the UK, STATCOMs or SVCs (see Chapter 4.4) are mandatory to include in wind farms. This is primarily intended for reactive power compensation but, as previously mentioned, STATCOMs and SVCs can also mitigate flicker and improve the voltage dip ride-through capabilities of the power system. In Sweden network owners usually use passive components – usually capacitor banks – on high voltage levels for reactive power compensation and technologies like STATCOMs and SVCs are very rarely used. A more widespread use of these technologies might make achieving effective reactive power compensation in the power system cheaper and easier than it is today and in the process make flicker and voltage dip mitigation easier; even though problems with these disturbances are currently not very common. This alternative approach requires cooperating with wind farm operators and to allow them to mitigate these problems in their installations, where it might sometimes be easier and cheaper. However, this may potentially also introduce a number of issues regarding the responsibility structure and stability of the power system. [21,22,23,35]

8.1. The Future of Wind Power

There is a continuous global increase in installed wind power. In 2011 the total installed capacity increased with 20 %, which was also an increase of the annual growth with 6 %. In the EU and the USA this increase is fueled mostly by goals set for what percentage of the electricity produced should come from renewable energy sources in the future. In the EU a binding target of 20 % renewable energy by 2020 was set in 2007. In the US the goal is 25 % renewable energy by 2025. Combined the EU and the US represent 39 % of the world's energy production, but the energy production in other areas of the world is steadily increasing. In 2011 the majority of the new wind power was installed outside of the EU and the US for the second year in a row. India, China, Brazil, Canada and Mexico are some examples of countries building large amounts of wind turbines today. In Sweden a goal was set in 2007 for 30 TWh of electricity produced by wind power per year by 2020. In 2007 the about 900 existing wind turbines in Sweden produced only a little more than 1 TWh per year, but by the end of 2010 the then 1665 existing turbines produced 3.5 TWh per year. This rapid increase and these ambitious goals mean that the wind power industry will have favorable conditions for investing in improved turbine technologies in the coming years. [11,37,38,39]

Turbine topologies replace each other at a high rate in the wind power industry. For example, Siemens started selling full-converter turbines with induction generators in 2004 after only having produced fixed-speed turbines and narrow range variable-speed turbines before. This new technology completely replaced the older turbine types at Siemens within a few years. In 2010 Siemens started selling full-converter turbines based on gearless multi-pole synchronous generators. This new full-converter type is expected to lead to a phasing out of the induction generator type full-converter turbine in just a few years from now. And, judging from the developments of the last decade, by then a new technology might very well have surfaced which in time will replace the synchronous generator type full-converter turbine. [16,24]

One new topology being researched right now uses the transverse flux machine (TFM) as a generator. The TFM is a permanent magnet machine with a rather complex design where, as the name suggests, the magnetic flux moves mainly transversally compared to the rotation of the rotor. In a TFM the magnetic flux moves in three dimensions and this places new demands on the magnetic material of the machine’s core. So called soft magnetic composites (SMCs) are often used to make magnetic cores which are capable of conducting flux in three dimensions. SMC materials are comprised of compressed metal powder particles. Besides being able to conduct flux in three dimensions the advantages of SMCs include the manufacturing process producing minimal waste and that copper recycling when the material has served its purpose is very easy. However, SMCs are brittle and some of the electric properties are less appealing than those of more traditional magnetic materials (e. g. low unsaturated permeability and high hysteresis losses). [17,40,41]

Figure 30 shows a segment of the stator and rotor of two types of TFMs, single-sided and double-sided. As can be seen the structure is quite complex, especially for the double-sided TFM with its two air gaps and a stator enveloping the rotor on two sides (see Figure 30 b)), and the TFM has therefore been regarded as very difficult to manufacture. However, the TFM has very high torque density, potentially making it possible to reduce the weight of the generator by two thirds compared to an induction generator for wind power applications, which creates an incentive for trying to perfect an economically viable manufacturing method. A problem with the TFM, though, is that it has a relatively low power factor; especially the single-sided TFM. An EU funded project, due to be concluded in 2013, is currently researching the TFMs applicability for wind turbines. [17,40,41]

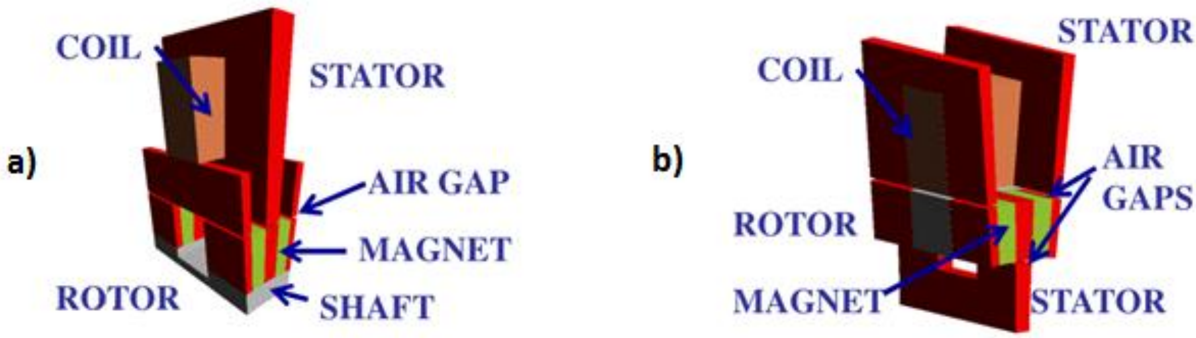

Figure 30. a) Single-sided TFM (with 60 poles). b) Double-sided TFM (with 60 poles). [41]

The switched reluctance machine (SRM) is another new generator alternative. This machine works by having a design with salient poles on both the rotor and the stator to create a different reluctance in the machine's magnetic circuit at different rotor positions. In a switched reluctance motor the rotor will then rotate to try to minimize the reluctance by perfectly aligning the rotor poles with the stator poles. By designing an SRM with a different number of poles in the rotor than the stator – commonly four rotor poles and six stator poles (see Figure 31) – perfect alignment becomes impossible. As can be seen in Figure 31 the rotor is aligned perfectly with pole pair "c" of the stator but an angle of β away from being aligned with the pole pair "a". In a switched reluctance generator a current is induced due to the continuously changing inductance of the stator windings caused by the changing reluctance of the generator's magnetic circuit as the rotor rotates. This will create current pulses in the windings of the stator pole pairs. If only one pole pair conducts current at a time and the pole pair coupled to conduct is switched with a certain interval using a frequency converter a switched reluctance generator will produce a constant DC current, which can then be fed to the grid through an inverter. [31,40]

Compared to the TFM, or even the induction machine, the manufacturing process for the SRM is very simple and cheap. No permanent magnets or rotor windings are required which also cuts down on material costs. Furthermore, the SRM has low inertia and is easy to repair. Disadvantages of the SRM include the need for a small and very uniform air gap, much scrap produced during manufacturing, and that a shaft position sensor is often required. [31,40]

The aim with new topologies for wind power applications is mainly being able to manufacture more cost effective and bigger wind turbines. Saving weight is necessary to make the nacelles of turbines with very high power ratings transportable. As previously mentioned, the nacelle of a 6.0 MW gearless turbine with synchronous generator weighs the same as a 3.6 MW full-converter turbine with an induction generator and a gearbox. Using TFMs or SRMs it might be possible to build even higher rated turbines without the nacelles becoming too bulky or heavy to handle. [24,31,40,41]

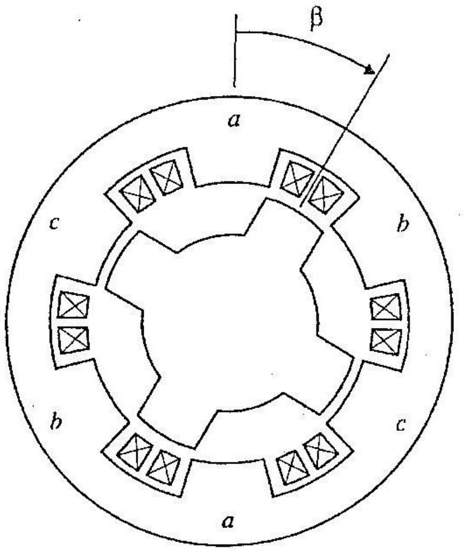

Figure 31. SRM with four rotor poles and six stator poles. [40]

There are also new developments regarding the topology of the converters. New types of semiconductor switches are for example being continually researched. The integrated gate-commutated thyristor (IGCT) is a potential replacement for the GTO as the first choice for handling high currents without requiring extra steps of protection. IGCTs have already been tested in wind turbines but not yet gained a lot of traction on the market. Also, there is research being conducted into bidirectionally conducting IGBTs (which could further simplify the converter circuit by making it possible to omit or at least downsize the freewheeling diodes). Semiconductors based on silicon carbide, instead of silicon, would provide many opportunities if made available. SiC can operate at very high temperatures and power ratings and has ten times the breakdown strength of silicon, which offers the possibility of much lower losses and consumption of material. However, SiC power electronics are very difficult to manufacture, which is why this material has not yet replaced silicon even though the advantages of SiC have been known for decades. Both obtaining the SiC crystals and making a substrate of suitable quality for making SiC semiconductors is problematic, which is why SiC semiconductors are not yet commercially available on a large scale. [42,43]

Attaching energy storage devices to wind farms to be able to make better use of the intermittent power generated has long been a goal in wind power research. There are a number of available energy storage devices (see Chapter 4.1.4) but none of them are currently able to provide enough storage capacity for this application. It is not yet cost effective to store the energy from an entire large wind farm for a time long enough to be able to compensate for a period of no wind when the consumption is high. An energy storage device able to provide 1 MW for 30 min should be considered top of the line today and this is only enough to help smooth out changes in generation due to varying wind speeds – not to replace the wind farm during a period of wind speeds below the cut-in wind speed. If the storage capacity of available storage devices should increase in the future such devices may advantageously be connected at the DC link of the converters. The development of such energy storage devices would eliminate a major obstacle to wind power being a dominant source of energy – the intermittency. [11,44,45]

What kind of impact these possible future developments of wind power could have on power quality disturbance mitigation is hard to say. New turbine topologies might generate different disturbances and they will also require new converter topologies which will then also generate different disturbances than the converter types commonly used today. New semiconductor switches or better energy storage capabilities of the converters could potentially improve converter performance, with respect to both losses and power quality mitigation, and the continued growth of the wind farm industry will guarantee that the research into these possible areas of improvement will continue.

8.2.The Future of the Power System (Smart Grid)

The current layout of the power system was designed decades ago. This means it is not designed to handle some of the modern additions to the power system, such as production facilities and loads containing power electronics. When the power system was designed the only concern with regard to power quality was availability; i. e. the only power quality disturbance considered was interruptions. Over the years the knowledge of power quality has increased and with it the awareness of how other disturbances can also affect the reliability of electric power. These other disturbance types, such as harmonics and flicker, were not at all considered when the power system was designed but the sources of these disturbances, such as wind farms and non-linear loads, are increasing in number in the power system. Therefore, new ways of structuring the power system are now being researched which would be more suitable to current and estimated future requirements. [6]

Distributed generation is a phenomenon that was not considered when the power system was designed. The standard division of a power system into generation, transmission, and distribution was made because when the system was designed the generation was done almost exclusively in large production facilities, often far from the majority of the end-users. The relatively new focus on renewable energy sources, such as wind farms and photovoltaic systems, has lead to an increase in production facilities of a wide range of sizes and often placed much closer to population centers. Therefore, most new power generators are now being connected directly to both the transmission and distribution parts of the power system rendering the traditional power system division more and more obsolete. This puts new strain on these parts of the power system but restructuring the grid has until now not been required, reinforcing it has sufficed. However, if the amount of distributed generation in the future should become too great or when a new area of the grid is to be designed a new grid structure might have to be considered. [8,9,44]

Smart grid is a broad and loosely defined term for a power system structure that is able to handle large amounts of distributed generation and increased usage of plug-in electric vehicles (PEVs) as well as utilize new technologies for communication, measurements and control. Also, a smart grid should be designed to facilitate bidirectional power flow; i. e. any installation connected to the system should be able to both consume and produce electric power, both draw power from and supply power to the grid. Much can be said about smart grid but here only a brief description of a smart grid structure will be given: [44,45,46,47]

A common basic structure of a smart grid is built around a voltage controlled bus. This can be either a DC- or an AC-bus and it is connected to the main power system. To this main bus all large distributed generators are connected as well as energy storage devices to smooth out the voltage and compensate for the intermittent qualities most distributed generators possess. A network of charging stations for PEVs can also be connected to the bus and through this network the PEVs can both be charged and also aid in compensation for voltage drops or consumption peaks by allowing the grid to temporarily use the PEVs' batteries as complementary storage devices. Large composite distributed generators like wind farms can have subsidiary buses of their own with their own storage devices attached. [44,45,46]

The local loads are connected to other subsidiary buses. These buses are prepared for connection of small distributed generators and the aim is to have many end-consumers producing power as well, mostly from small wind turbines or solar panels, and feeding this power to their buses. Also every house should be prepared for connection to the PEV charging network. An advanced system for measuring and controlling the network has to be implemented for this smart grid structure to be able to be used. [44,45,46]

Wind farms are today very seldom actively used in power system regulation. They are usually considered only as negative loads and cannot be controlled by the system operators. A new method for better usage of distributed generation in power system control is virtual power plants (VPPs). A VPP is formed by enabling the system operators to control distributed generators and grouping them to form a VPP of such size that controlling it can significantly impact the power system. The largest wind farms can be their own VPPs, but you can also form VPPs from a variety of smaller wind turbines and photovoltaic systems etc. at a distribution level of the power system. Here controllable loads can be included in the VPPs as well. The participation of distributed generation in the energy market can also be facilitated through use of VPPs. [45,46,47]

Micro grid is another broad and loosely defined term related to smart grids. Some futuristic visions of the power system see the traditional power system replaced by small micro grids operating completely autonomously and supplied exclusively by distributed generation. Others define a micro grid as a small portion of the distribution level of the traditional power system that has such a saturation of distributed generation that it can function autonomously from the main grid if needed. The latter operational mode requires energy storage devices to aid in frequency and voltage regulation and places high demands on the control system, which must be completely restructured compared to the control system for a traditional grid. [45,46]

An example of a project where a smart grid is being implemented in an urban area is Stockholm Royal Seaport (SRS; sv: Norra Djurgårdsstaden) which is currently under construction in central Stockholm. SRS will become a fully functional urban district with 10 000 apartments and around 30 000 workplaces and the aim is for the district to be completely free from fossil fuels when it is finished in 2025. Household will be actively contributing to the energy market through PEVs and their own distributed generators and this will potentially eliminate peaks in electricity consumption and thereby lower the required production capability compared to a traditional grid structure. Central energy storage will be implemented as described above and charging stations for PEVs will be constructed throughout SRS. Also, a smart grid research laboratory will be built and, since SRS is located in a harbor district, grid connection of large ships will be enabled to prevent them from having to run on generators while docked. Special attention will also be paid to data collection and information management to facilitate further research into smart grid technology. [48]

If the structure of the power system was changed according to the above descriptions the effects on mitigation, as well as all other aspects of power system operations, could be massive. The smart grid is a much more actively controlled system than the traditional power system and therefore both the disturbance emissions and the mitigation techniques could change drastically if a smart grid structure was implemented on a large scale. Equipment like UPS systems, active filters, SVCs, and STATCOMs could be much more easily integrated into a smart grid structure. If the main buses of the smart grid would be DC-buses then the properties of the grid and the approach to mitigation would be even more different from those of the current system. [44,45,46,47]

9. Discussion & Conclusions

In the aim of this thesis it is stated that a connection between academic theories about power quality disturbance mitigation and the way disturbance mitigation is actually handled in the Swedish power system when building new wind farms should be made. This aim has resulted in a very different focus of the thesis than would a stronger reliance on academic literature. Without the material collected from interviews with representatives from the Swedish power system industry the relative focus placed on active and passive mitigation devices would have been quite different. The academic literature gives a lot of space and credit to various active devices which the power system companies view as being too expensive, complex, and as though their continued existence is uncertain due to the rapid development in the field. Also, the fact that harmonics are virtually the only disturbance type requiring any mitigation in reality is not entirely clear in the academic literature, where all known disturbance types are sometimes given equal space or at least not an amount of space proportional to the frequency with which they occur in the power system.

After considering the information from the power system industry the main focus of the report came to be on passive filters, since these are the overwhelmingly dominant mitigation devices for harmonics, and harmonics in turn is the overwhelmingly dominant disturbance type in the Swedish power system. The filters are primarily placed internally in the converters of the full-converter wind turbines – which are the turbine types exclusively used today in large wind farms – but complementary filters can also be placed externally. Even though a broad range of active mitigation devices exist, they are so rarely used in production facilities that they were not considered relevant to explain any further than in the brief review of mitigation devices in Chapter 4. Measurements of and grid response to disturbances – especially flicker and harmonics – were given some space in the report, since these areas seem to be central to the handling of disturbances in wind farms in practice.

The total dominance of passive filters placed internally in the turbines combined with the secrecy policies of turbine manufacturers resulted in the investigation of whether to create a computer-based tool for choosing mitigation method yielding no significant advantages of such a tool and therefore no tool was designed.

It has been difficult finding reasons why SVCs and STATCOMs are not used more in the Swedish power system even though they have clear advantages in both reactive power compensation and disturbance mitigation. Possibly, one reason could be that the network owners would have to outsource the stability of the power system to the wind farm operators too much. Being too dependent on parties in the power system which do not necessarily have the same priorities and do not consider the same long time-spans could potentially compromise the stability of the grid in the long term. Also, the Swedish power system is a very stable one and therefore changing its way of operating may seem unnecessary.

As demonstrated in Chapter 8 above the future of mitigation, in wind farms or in general, could involve big changes for a number of reasons. If any of the new turbine topologies, semiconductor switches, or power system structures discussed in Chapter 8 will replace currently dominant technologies in the future is very hard to say. Pilot projects are underway for several of the new technologies mentioned but even if a new technology is proven superior in some respects to one of the currently dominant ones there are still many things that could hinder a shift of technologies. For example, the ability convince investors to switch to the new technology and perfecting a cost-effective manufacturing process might prove difficult, or in the case of smart grid the entire power system needs to collectively support a change for it to become dominant.

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