Voltage Source Converters with Energy Storage Capability

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Stockholm 2006
Submitted to the School of Electrical Engineering in partial fulfillment of
the requirements for the degree of Licentiate.

Stockholm 2006

ISBN 91-7178-523-X
ISSN 1653-5146
TRITA–EE 2006:057

This document was prepared using \TeX.
Preface

The work presented in this thesis was carried out at the Division of Electrical Machines and Power Electronics, School of Electrical Engineering, Royal Institute of Technology (KTH). This project is financed from the Competence Center in Electric Power Engineering (EKC$^2$) at KTH and is one of the ongoing projects within the research program of Controllable Power Systems at EKC$^2$.

The main contributions of this work can be summarized as following:

- A novel flux modulation scheme combined with a deadbeat current control strategy has been developed for two level Voltage Source Converters (VSC). By this control system, both the positive and negative sequence components of the converter current and bus voltage are controllable [1].
- Effective active power compensation schemes have been proposed for improvement of the power quality at the Point of Common Coupling (PCC) in power systems and for performance enhancement of certain phase sensitive applications [2].
- The impact of energy storage on the performance of a certain system under fault conditions has been investigated [3].
- The possible use of a Static synchronous Compensator (StatCom) with energy storage to improve the power quality at the PCC of a system with cyclic loads has been studied (Chapter 6).
Abstract

This project deals with voltage source converters with energy storage capability. The main objective is to study the possible benefits of energy storage to a power system with a VSC as the interface between them.

First of all, a converter control system is proposed for a two level VSC. In the conventional converter control, the control system usually takes the voltage measured at the point where the converter is connected and calculates the reference voltage for the converter; with a modulation system the converter then produces the required 'average voltage'. In this project, a novel flux modulation scheme, combined with the deadbeat current control strategy, is proposed. The current controller is capable of controlling both positive and negative sequence current components. With flux modulation, the control system measures the bus flux and commands the converter to generate the required flux.

Based on the proposed control strategies, several application studies have been carried out.

The first application study investigates the effect of energy storage on the power quality at the point of common coupling when a system is subject to load disturbances. The voltage at PCC in a weak network is very sensitive to load changes. A sudden change in active load will cause both a phase jump and a magnitude fluctuation in the bus voltage, whereas reactive load changes mainly affect the voltage magnitude. With the addition of energy storage to a StatCom, it is possible to compensate for the active power change as well as providing reactive power support. In this thesis, some effective active power compensation schemes are proposed. Simulations and experiments have been performed to verify the compensation schemes.
results show that a StatCom with energy storage can significantly reduce phase jumps and magnitude deviations of the bus voltage.

The impact of the energy storage on the performance of weak systems under fault conditions has been investigated. The investigation was done by studying an example system. The system model was established based on a real system, in which some induction motors driving pumps along a pipeline are fed from a radial transmission line. Studies show that for a weak system with induction motor loads, a StatCom with certain energy storage capacity will effectively improve the system recovery after faults. Although this incurs extra cost for the increasing dc voltage rating and size of the dc side capacitor, the overall rating of the converter can be reduced by utilization of the proposed active power compensation scheme.

The last case study investigates the possible use of a StatCom with energy storage to improve the power quality at the point of common coupling where a cyclic load is connected. Studies show that by providing both fast reactive and fast active power support to the network, not only the voltage magnitude can be well controlled, but also the voltage phase jump can be reduced significantly.

Keywords

- Voltage source converter
- StatCom
- Energy storage
- Active power compensation
- Phase jump
- Voltage dip
- VSC
- Weak network
- Flux modulation
- deadbeat control
Acknowledgment

The financial support from the Competence Center in Electric Power Engineering at KTH is gratefully acknowledged. Moreover, many people have been involved in or helped with this project work and I hereby kindly acknowledge them.

First of all, I would like to thank my supervisor Prof. Lennart Ångquist for his patient and thorough guidance, from the theoretical analysis to the painstaking practical work with the real-time simulator, and for revising and proof reading this thesis again and again.

I also would like to thank my supervisor Prof. Hans-Peter Nee for his supervision, his invaluable discussion and continuous encouragement, especially for proof reading my thesis during ‘pappaledigt’.

My thanks also go to Dr. Valerijs Knazkins for communicating with the steering committee about the progress of the project.

I am grateful to Prof. Stefan Östhund for introducing me into EME in the very beginning and to Prof. Chandur Sadarangani for his encouragement. Jan Timmerman and Jan-Olov Brännvall are acknowledged for their help with my work in the laboratory; Eva Pettersson and Margaretha Surjadi are acknowledged for their help with all those economic and administrative matters; Peter Lönn is acknowledged for keeping my computers working and for solving all the software problems.

I also would like to thank my good friends Tech. Lic. Robert Chin and Dmitry Svechkarenko for all their help, especially the great help with Latex. Thank Tech. Lic. Paulo Fisher, Tommy Kjellqvist and Dr. Staffan
Norrga for sharing offices and their knowledge with me. Thank Tech. Lic. Mats Leksell, Tech. Lic. Stephan Meier and Nicklas Johansson for the interesting discussions. I would like to convey my thanks to all the members of EME for the friendship and for creating a wonderful working atmosphere.

Some people from ABB are acknowledged here. Thank Mr. Åke Petersson and Mr. Jean-Philippe Hasler for the valuable discussion and for providing the model parameters used in Chapter 5. Thank Mr. Lennart Wernersson for the help with the Mach2 control system in the real-time simulator. Thank Dr. Jan Svensson for the interesting discussions.

Many thanks to my big family: my parents, my mother in law, my brothers and sisters, my nephews and nieces, for their love and support.

Finally, I will send my deepest gratitude and love to my small family: my husband Guangjie and my daughter Bingxi. Thank you so much for your endless love, support, and especially for your understanding.

谢谢您们！

Hailian Xie

Stockholm, November, 2006
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1 Introduction

Energy storage is playing an increasingly important role in the electrical power system thanks to the development and advance in various energy storage and power electronics technologies in recent years. On the other hand, the increase in electrical load, the tendency to operate the power system closer to its limit, and the associated reliability issues are driving the development of the energy storage technologies and their applications.

1.1 Various Energy storage technologies

Although electricity cannot be stored, the energy can be converted into and stored in different forms: electromagnetic, electrochemical, kinetic or as potential energy. Based on these energy forms various energy storage technologies have been developed or are under development:

- Battery
- Super Capacitor
- Flywheel
- Superconducting Magnetic Energy storage (SMES)
- Compressed Air Energy Storage (CAES)
- Pumped Hydro Storage

Battery is the oldest form of energy storage and the currently available battery technologies are based on either conventional battery technologies or flow battery technologies.
Among the conventional battery technologies, the lead-acid battery is the most developed one and has been in use for more than 100 years. However, it has a short life and poor reliability. The world’s largest lead-acid battery energy storage system rated at 40 MWh was installed in Chino, California in 1988 for load leveling and peaking [4].

The sodium Sulfur Battery, known as NaS, is characterized by long cycle life, high energy efficiency (up to 86%), high specific energy (3–4 times a lead-acid battery), and very low self-discharge rates. NaS batteries have a pulse power capability over six times their continuous rating (for 30 seconds), which enables the NaS battery to be economically used in combined power quality and peak shaving applications [5]. There have been over 30 installations in Japan.

The nickel cadmium battery is a mature technology and a Ni-Cd battery energy storage system with 46 MW for 15 minutes has been in operation in Fairbanks, Alaska from late 2003 [6].

The nickel metal hydride battery has very low potential use in the utility scale due to the extremely high cost.

Rechargeable Metal-air batteries and large scale lithium based batteries, such as the Lithium ion Battery (Li-ion), the Lithium Ion Polymer, and the Lithium Metal-Polymer, are still under development [7].

An emerging technology, the ZEBRA battery, is designed especially for electric and hybrid vehicles. ZEBRA batteries are high temperature batteries with an energy density four times as high as that of lead acid batteries. In addition to high energy density, high energy efficiency, zero gaseous emission, and compactness make the ZEBRA battery very attractive for stationary applications. One of the first applications of this type is the two 557V 32Ah ZEBRA batteries installed in the CESI DISPOWER Test Facility controlling the voltage of the grid both in the case of desired and undesired electrical islanding [8].
1.1 Various Energy storage technologies

The conventional battery technologies mentioned above are usually designed for either high power with short discharge duration or low power with long discharge duration, whereas the power rating and energy rating of flow battery technologies are independent of each other. The energy rating of a flow battery can be increased by increasing the storage bank and the power rating is dependent on the power electronics connected to the battery. Leading flow technologies include: Polysulfide Bromide flow Battery (PSB, or Regenesys), Vanadium Redox Flow Battery (VRB), Zinc Bromine Flow Battery (ZnBr), and Hydrogen Bromine (H-Br) batteries.

Super Capacitor is also called Ultra Capacitor, Electrochemical Capacitor, or Advanced Capacitor. In a super capacitor, the energy is stored electrostatically in two series capacitors, one formed by the electrolyte ions and the positive electrode and the other one formed by the electrolyte ions and the negative electrode. As in a conventional capacitor, no chemical reaction occurs in energy delivery. While the small electrochemical capacitors are well developed, the larger units with energy densities over $20 \text{kWh/m}^3$ are still under development [9].

In a flywheel energy storage system, a flywheel is coupled to an electrical machine that interacts with the grid through power electronics. Energy is stored when the machine operates as a motor to turn the flywheel and is released upon demand when it works as a generator to convert the stored kinetic energy into electricity. Flywheel technology began over 100 years ago and has proved to surpass chemical batteries for many applications in the 1990’s [10].

Pumped Hydro Storage uses two reservoirs, one on the base level, and the other with a certain elevation. Water is pumped up to the upper pool at off-peak time and is reversed to the lower pool through a hydraulic turbine to generate electrical power upon demand. The first pumped hydro storage system began operation in 1929 [11]. In 1999 the EU had 32 GW capacity of pumped storage out of a total of 188 GW of hydropower and representing 5.5 % of the total electrical capacity in the EU. In 2000 the United States had 19500 MWe capacity of pumped storage [12].
Compressed Air Energy Storage has been in commercial use since 1978. In a CAES, air is compressed by using low-cost electricity and stored in underground caverns. When required, the compressed air is released and the expanded air drives gas turbines to produce electricity.

SMES was first proposed as an energy storage technology in the 1970s although the superconductor was discovered already in 1911 [13]. A SMES unit stores energy in the magnetic field created by the dc current through the superconducting coil.

Energy storage devices are characterized by their power rating and energy rating. Fig. 1.1 gives a clear picture of these characteristics of most of the energy storage technologies stated above.
1.2 Energy storage applications

The large variety of energy storage technologies makes their application possible for various purposes, which can be identified and classified into three categories with several applications in each of them. At the generation level, there are applications for rapid reserve, area control and frequency reserve, and commodity storage. Transmission and distribution applications include transmission system stability, transmission voltage regulation, transmission facility deferral, and distribution facility deferral. Renewable energy management, customer energy management, and power quality and reliability are in the customer service category [14] [15]. Although the functions of energy storage are organized into different categories and the implementation of energy storage might be committed by different business units, energy storage will benefit the most when it serves multiple functions. For instance, the battery energy storage system installed in Golden Valley Electric Association was designed for functions of Var support, spinning reserve, power system stabilization, Automatic Scheduling, Support for Scheduled Load, and Automatic Generation Control [16].

The requirements on power and energy rating of the energy storage devices depend on the applications that these devices are used for. While in some applications a high power with short discharge duration is desired, in others a low power and long duration are required. Fig. 1.2 depicts the requirements of different applications listed above.

In recent years, the application of energy storage to improve transmission system stability and to enhance power quality and reliability has drawn increasing attention as a result of the higher power quality required by the ever more sophisticated electronic devices used by industrial and commercial customers. In these applications, voltage source converters are usually deployed to interface the energy storage devices with the power system.

The possible application of energy storage for damping of power system oscillations has been intensively investigated. Power oscillation occurs when there is a trip of transmission lines, loss of generation, or large changes in electric
Studies in [4] show that an energy source power system stabilizer can provide damping of power swings by modulating the power output/input of the energy storage batteries to respond to the system frequency deviations caused by oscillations. Some other different control schemes have been studied (e.g., [17, 18, 19, 20]), showing enhanced performance of StatComs in damping of power system oscillation by the integration of energy storage.

Work also has been done to investigate the utilization of energy storage for the improvement of power quality and reliability. Voltage sags, usually caused by faults in the electrical system, are the most common disturbances in power systems and thus cause very much concern. Voltage sags can also occur during the start up of large motor loads or during the operation of special electrical equipment such as welders, arc furnaces, smelters, etc. It is reported that a dynamic voltage restorer with energy storage can effectively
mitigate voltage sags by injecting required voltage in series with the source voltage [21]. Other control strategies that can be used in an integrated voltage source converter and energy storage system for the purpose of voltage sag mitigation have also been discussed, e.g., in [22, 23].

1.3 Project objective

This project investigates the possible benefit of energy storage to power systems when the energy storage is integrated in a StatCom. Voltage source converters can be used to interface the energy storage to the power system. As the basis of the investigation, proper control strategies should be developed. Then several case studies should be carried out to verify the control strategies and to investigate the impact of the energy storage on power systems in following aspects:

- The power quality at the point of common coupling (PCC) when the system is subject to disturbances.
- System performance under fault conditions.

The investigations should be carried out in power system simulation software PSCAD and in the real-time simulator if applicable.

1.4 Outline of the thesis

Chapter 2 gives an overview of the investigated system model and the real-time simulator.

Chapter 3 describes the converter control system, including the inner current control, flux modulation scheme and the outer power control loop.

Chapter 4 presents a case study regarding the power quality at the PCC under load disturbances.

Chapter 5 presents a case study to show the impact of energy storage on system performance under fault conditions.
Chapter 6 presents a case study of a system with cyclic load.

Chapter 7 concludes the investigations and gives suggestions for future work.
2 System Overview

2.1 System configuration

Although multilevel voltage source converters have certain advantages over two level converters such as higher voltage and power rating, better output voltage waveform, less electromagnetic interference, etc. [24], the control system is much more complicated. Since the focus of this project is the effect of the energy storage connected on the dc side of converters, two level voltage source converters will be utilized to interface the energy storage to power systems. The energy storage devices used in the investigations are conventional large capacitor banks. The voltage source converters are connected to the power system at the PCC through phase reactors, which also serve as filter inductors. Filters are necessary to prevent harmonics from spreading into the network. Also connected at the PCC are various loads, which are parts of the investigated systems. The system configuration is depicted in Fig. 2.1.

Figure 2.1: System overview
2.2 Design of Converter Filter

Fast switching of the converter bridge creates high frequency harmonics in the converter output voltage. In order to prevent these harmonics from getting into the network, a filter must be properly designed and utilized.

In [25], a filter configuration as shown in Fig. 2.2 is recommended specially for PWM inverters.

In the figure, $u_v$ stands for the converter output voltage and $u_b$ for the network bus voltage at the converter connection point.

In case that the converter is connected to the network through a phase reactor $L_v$, the phase reactor can be used as the series filter inductor.

The filter consists of two parts. The right parts, the combination of the series inductor and the filter capacitor, gives a high reduction of the high frequency component and low reduction of the fundamental frequency. However, a resonance occurs at a certain frequency $f_{01}$. In order to avoid the amplification of any harmonic components, this resonance frequency should be chosen lower than the lowest harmonic frequency that might appear in the output voltage. On the other hand, a parallel branch with the same capacitance is added as the left part of the filter to damp out this resonance. The resonance frequency $f_{02}$ of the parallel branch is empirically
2.2 Design of Converter Filter

chosen as half the series resonance frequency $f_{01}$ and the resistance as $\frac{x_{01}}{0.442}$ with $x_{01}$ representing the reactance of the phase reactor at frequency $f_{01}$.

For a switching frequency of 1350 Hz ('triangular frequency'), which is always used in the simulations and the real-time simulator throughout this project, the first set of harmonics generated by the converter has the orders of $n = p \pm 2m, m = 1, 2, 3, \ldots$. Where $p = 1350/50 = 27$ is the frequency modulation ratio. In order to get adequate reduction for the lower order harmonics, a series resonance frequency $f_{01}$ of 350Hz is chosen.

The frequency response of the filter designed for this switching frequency is depicted in Fig 2.3. The gains at fundamental frequency and at the switching frequency are 1.03 and 0.08 respectively.

Figure 2.3: Converter filter frequency response
2.3 Real-time Simulator

In the laboratory of the Division of Electrical Machine and Power Electronics at KTH, a two level voltage source converter has been built up in a real-time simulator. The converter utilizes $10\sqrt{3}V$ rms as the nominal line-line voltage and 8VA as the nominal power. Inductors, resistors and capacitors are used to represent the transmission lines in the power system. The generators are modeled by electronic power amplifiers controlled by DSPs. The simulator contains an ABB Mach 2 control system, which is adapted to control power electronic apparatus for high-power applications.
3 Control Strategies

When a voltage source converter is connected to a grid as a StatCom without energy storage, the power flow between the converter and the grid should be controlled such that the voltage at the connection point is maintained at a certain level and at the same time the converter dc side voltage is kept at a reasonable and relatively constant value to ensure a successful converter operation. The power control of a three-phase Pulse-Width Modulated (PWM) converter can be achieved either with or without an inner current control loop. Power control without the inner current control loop is usually called Direct Power Control [26]. However, current control has been broadly applied in the control of three-phase PWM VSCs due to its capability to provide fast and accurate converter output control as well as peak current protection. Among all the current control strategies, deadbeat control is probably the most effective one and is widely used. Therefore, an inner current deadbeat control loop is employed in the converter control in this project. In addition, a novel flux modulation scheme is utilized for the switching control of the converter bridge. This chapter gives detailed description of the flux modulation scheme combined with deadbeat current control and the power control of voltage source converters.

3.1 Flux Modulation and Deadbeat Current Control

The essence of deadbeat control is to control the converter current to follow the reference value with one sampling period delay disregarding the computational delay introduced by the digital control system. This control technique has been extensively investigated [27, 28, 29, 30], with the current vector oriented with respect to the line voltage vector.
Conventionally, the current vector is oriented with respect to the network voltage vector and the PWM system works with the converter reference voltages. However, by considering the utility grid as a virtual electrical machine, the current vector can be oriented with respect to the virtual flux of the grid, which is constructed by integrating the grid voltage [31]. The original idea to control the machine flux directly in order to control the torque (or power) was first presented by Depenbrock in 1985 [32, 33]. Later Takahashi and Ohmori presented a modified version [34], in which the preferred flux path was a circle instead of the hexagon used in [32]. Both of these methods were based on hysteresis control. The virtual flux concept has also been reported in other works. A current control scheme based on virtual-flux orientation was proposed in [26], in which the estimated virtual flux vector provided the angle used in the coordinate transformation by both the line current and the converter reference voltage. The Direct Power Control method uses the estimated virtual flux to estimate instantaneous power flow in the system [35]. In [36], the converter virtual flux magnitude is controlled, which, together with the angular difference between the virtual fluxes of the grid and the converter, determines the switching state of the converter by using a look-up table. A flux modulation approach is proposed in [37], which examines the movement of the converter flux and selects the corresponding switch action according to a set of switching rules. Another flux vector modulation strategy proposed in [38] takes the desired motor stator flux vector as reference and calculates the switching times so that the output flux vector can follow the reference.

In this project, a new control scheme combining flux modulation and deadbeat current control has been developed. Additionally, the current controller is capable of controlling positive and negative sequence current components as well as offset. The flux of the grid can be obtained by physically integrating the grid voltage, e.g., using a passive RC filter, and the VSC is controlled to generate the virtual flux needed to drive the desired current flowing between the converter and the grid. The use of integrators makes the system less sensitive to harmonics, measurement noise and disturbances in the network.
3.1 Flux Modulation and Deadbeat Current Control

3.1.1 The Converter Virtual Flux

For a two-level voltage source converter shown in Fig. 3.1, the coupling function associated with phase \( x \) (\( x \) represents a, b and c when phase quantities are concerned throughout this work) can be defined as

- \( K_x = 0 \) when terminal \( x \) is connected to the lower dc rail
- \( K_x = 1 \) when terminal \( x \) is connected to the upper dc rail

With this definition, the ac voltage generated by the converter can be described as a space vector in the \( \alpha\beta \) plane:

\[
\vec{u}_{\alpha\beta} (t) = \frac{2}{3} \left\{ K_a (t) + e^{j \frac{2\pi}{3}} K_b (t) + e^{-j \frac{2\pi}{3}} K_c (t) \right\} u_d
\]  

(3.1)

All the quantities used in the equation and the equations hereafter are in physical units unless otherwise stated.

It is obvious that the voltage vector will adopt one of the seven different values corresponding to eight different combinations of the coupling functions \( K_a, K_b, \) and \( K_c \) (both 111 and 000 give a zero vector).

The converter virtual flux can be introduced by (3.2)

\[
\frac{d\vec{\psi}_{\alpha\beta}}{dt} = \vec{u}_{\alpha\beta} (t) = \frac{2}{3} \left\{ K_a (t) + e^{j \frac{2\pi}{3}} K_b (t) + e^{-j \frac{2\pi}{3}} K_c (t) \right\} u_d
\]  

(3.2)
Integrating (3.2) during one switching period \(< t_k, t_{k+1} >\) yields

\[
\Delta \overline{\psi}^{\alpha\beta} v, k = \overline{\psi}^{\alpha\beta} v(t_{k+1}) - \overline{\psi}^{\alpha\beta} v(t_k) = \frac{2}{3} \int_{t_k}^{t_{k+1}} \left\{ K_a(t) + e^{j2\pi/3} K_b(t) + e^{-j2\pi/3} K_c(t) \right\} u_d dt \quad (3.3)
\]

This means that the switching state can be determined by the flux change during one sampling interval.

In the \(\alpha\beta\) plane, tracing of the converter voltage vector always results in seven dots as shown in Fig. 3.2. On the other hand, the converter virtual flux moves along a circle with a number of steps depending on the switching frequency. The higher the switching frequency is, the closer the locus is to a circle.

In the next section, the current control, which gives the reference value of the converter flux change, will be described.
3.1 Flux Modulation and Deadbeat Current Control

3.1.2 Deadbeat Current Control

For purpose of demonstration of the flux modulation and the deadbeat current control system, the converter is connected to the PCC in the grid via phase inductors with certain reactance $x_v$ and resistance $r_v$, as shown in Fig. 3.3. This point is referred to as the 'bus-bar' in this work and the virtual bus-bar flux $\bar{\psi}_B$ represents the grid flux. The current controller operates with a fixed sampling interval, corresponding to twice the frequency of the triangular wave used in the 'carrier-based' PWM modulation scheme.

$$T_s = \frac{1}{2f_{tri}} \quad (3.4)$$

The target for the current controller is to control the positive and the negative sequence components of the fundamental frequency components of the converter current. Normally, there is no need to control the dc offset current. However, in order to measure the positive and negative sequence components of the current it seems advantageous to assume a dc offset component as well. This means that the current reference has the following form

$$i_{v,ref}^{\alpha\beta}(t) = i_{v,ofs,ref}^{\alpha\beta} + i_{v,p,ref}^{dq}e^{j\theta(t)} + i_{v,n,ref}^{dq}e^{-j\theta(t)} \quad (3.5)$$

Figure 3.3: Converter and the control system
Similarly, the bus-bar flux can be represented by a space vector with positive, negative and offset components, i.e., having the following form

\[
\vec{\psi}_B(t) = \vec{\psi}_{B,ofs} + \vec{\psi}_{B,d} e^{j\theta(t)} + \vec{\psi}_{B,n} e^{-j\theta(t)}
\]

\[
\dot{\theta}(t) = \omega(t) \quad (3.6)
\]

Equation (3.6) also shows that the concept of positive and negative sequence components inherently relies on the existence of a time function, \(\theta(t)\), which defines a coordinate system that rotates with the speed of the fundamental frequency components. A Phase-Locked-Loop (PLL) operating on the positive sequence component of the bus-bar flux is utilized to provide such a coordinate system reference.

The deadbeat current control in the virtual flux modulation system was based on the strategy that has been described in detail in [27]. In deducing the control algorithm it is assumed that the desired flux change in the preceding sampling interval has been delivered. Accordingly, the desired converter current will be obtained at the end of the preceding sampling interval. This means that the essence of the dead-beat control is to calculate the estimated converter flux change for interval \( < t_k, t_{k+1} > \) such that no additional error will be created.

With the indicated current direction the following formula applies

\[
\vec{\psi}_v(t) = \vec{\psi}_B(t) + x_v \vec{\tau}_v(t) + r_v \int_{-\infty}^{t} \vec{\tau}_v(\xi) d\xi \quad (3.7)
\]

It can be seen that when (3.7) is transformed into dq plane, there is no cross-coupling between d and q components associated with \( x_v \). Although these two components are still coupled through \( r_v \), which is usually 10 times smaller than \( x_v \), the cross-coupling effect is significantly reduced.

The flux change during one switching period \( < t_k, t_{k+1} > \) can be easily estimated by calculating the difference between the fluxes at the start and the end of the interval:

\[
\Delta \vec{\psi}_v(k) = \Delta \vec{\psi}_B(k) + x_v \Delta \vec{\tau}_v(k) + r_v \int_{t_k}^{t_{k+1}} \vec{\tau}_v(\xi) d\xi \quad (3.8)
\]
where the symbols with the 'hat' indicator on top, e.g. $\hat{\Delta \psi}^{\alpha\beta}$, denote the estimated values.

The three terms on the right side of (3.8) can be easily identified as:

- The flux change necessary to balance the bus-bar flux change.
- The flux change necessary to get the desired current at $t_{k+1}$.
- The flux change necessary to compensate for the resistive voltage drop.

To eliminate the steady state current errors, a PI controller is employed. This gives the fourth term of the converter flux change:

- Corrective flux change provided by the current controller.

Due to the computational time needed by any digital control system, the flux change in the interval $<t_k, t_{k+1}>$ will be calculated using the current reference values and other measured values available up to time instant $t_{k-1}$.

At sampling instant $t_{k-1}$, the vectors in (3.8) can be obtained together with the measured converter current and the actual value of the coordinate system angle and frequency. These values at $t = t_{k-1}$ are denoted $\bar{i}_{v,ofs,k-1}$, $\bar{i}_{v,p,ref,k-1}$, $\bar{i}_{v,n,ref,k-1}$, $\bar{\psi}_{B,ofs,k-1}$, $\bar{\psi}_{B,p,k-1}$, $\bar{\psi}_{B,n,k-1}$, $\bar{\theta}_{k-1}$ and $\bar{\omega}_{k-1}$.

The four terms can be calculated respectively as shown below.

**Required flux change to balance the bus-bar flux change**

At time instant $t_{k-1}$ the bus-bar flux vectors $\bar{\psi}_{B,ofs,k-1}$, $\bar{\psi}_{B,p,k-1}$, $\bar{\psi}_{B,n,k-1}$, the coordinate system angle $\theta_{k-1}$ and frequency $\omega_{k-1}$ are known. Then it is possible to estimate the flux at the start and the end of the sampling interval $<t_k, t_{k+1}>$ as

$$\hat{\theta}_{k|k-1} = \theta_{k-1} + T_s \omega_{k-1}$$

$$\hat{\psi}_{B,k|k-1} = \bar{\psi}_{B,ofs,k-1} + \bar{\psi}_{B,p,k-1} e^{j\hat{\theta}_{k|k-1}} + \bar{\psi}_{B,n,k-1} e^{-j\hat{\theta}_{k|k-1}}$$

(3.9)
and
\[\begin{align*}
\hat{\theta}_{k+1|k-1} &= \theta_{k-1} + 2T_s \omega_{k-1} \\
\hat{\psi}_{\alpha\beta}^{B,k+1|k-1} &= \hat{\psi}_{B,ofs,k-1}^{\alpha\beta} + \hat{\psi}_{B,p,k-1}^{\alpha\beta} e^{j\hat{\theta}_{k+1|k-1}} + \hat{\psi}_{B,n,k-1}^{\alpha\beta} e^{-j\hat{\theta}_{k+1|k-1}}
\end{align*}\] (3.10)

where the estimated values with double subscripts, e.g. \(\hat{\psi}_{B,k+1|k-1}\), denote estimations of the values of the complex vector \(\vec{\psi}_{\alpha\beta}^{B}\) at time \(t_{k+1}\) based on the information available at time \(t_{k-1}\).

Then the required flux change to balance the bus-bar flux change is:

\[\Delta \hat{\psi}_{\alpha\beta}^{B,k|k-1} = \hat{\psi}_{B,k+1|k-1} - \hat{\psi}_{B,k|k-1}\] (3.11)

**Required flux change to drive converter current through the phase inductor**

Assume that the phase inductor reactance is \(x_v\). At time instant \(t_{k-1}\) the current references are given in the rotating coordinate system as \(\vec{I}_{\alpha\beta,v,ofs,ref,k-1}\), \(\vec{I}_{\alpha\beta,v,p,ref,k-1}\), and \(\vec{I}_{\alpha\beta,v,n,ref,k-1}\). Due to the one-sample control delay and one-sample computational delay in a digital control system, a successful deadbeat control ensures that the current follows the reference value with two-sample delay. Hence the desired currents at time \(t_k\) and \(t_{k+1}\) are estimated based on the current references at time \(t_{k-2}\) and \(t_{k-1}\):

\[\begin{align*}
\hat{\psi}_{\alpha\beta}^{v,k|k-2} &= \vec{I}_{\alpha\beta,v,ofs,ref,k-2} + \vec{I}_{\alpha\beta,v,p,ref,k-2} e^{j\hat{\theta}_{k-2}} + \vec{I}_{\alpha\beta,v,n,ref,k-2} e^{-j\hat{\theta}_{k-2}} \\
\hat{\psi}_{\alpha\beta}^{v,k+1|k-1} &= \vec{I}_{\alpha\beta,v,ofs,ref,k-1} + \vec{I}_{\alpha\beta,v,p,ref,k-1} e^{j\hat{\theta}_{k-1}} + \vec{I}_{\alpha\beta,v,n,ref,k-1} e^{-j\hat{\theta}_{k-1}}
\end{align*}\] (3.12)

where \(\hat{\theta}_{k-2} = \theta_{k-2} + 2T_s \omega_{k-2}\).

The converter flux contribution required to force the desired current at time instant \(t_{k+1}\) is given by

\[\hat{\psi}_{I_{ref,k+1|k-1}}^{\alpha\beta} = x_v \hat{\psi}_{\alpha\beta}^{v,k+1|k-1}\] (3.13)
Therefore the estimated flux change is given by
\[
\Delta \hat{\psi}_{\alpha\beta}^{\text{ref},k|k-1} = T_v \left[ \hat{i}_{v,k|k+1} - \hat{i}_{v,k|k-2} \right] \tag{3.14}
\]

**Required flux change to cover resistive voltage drop**

The resistive voltage drop causes a loss of flux as given by the following expression
\[
\bar{\psi}_{R}^{\alpha\beta} (t) = \int_{-\infty}^{t} r_v \bar{\psi}_{v}^{\alpha\beta} (\xi) \, d\xi \tag{3.15}
\]

Thus, the estimated flux change in the interval \( \langle t_k, t_{k+1} \rangle \) is given by
\[
\Delta \hat{\psi}_{R,k|k-1}^{\alpha\beta} = r_v \int_{t_k}^{t_{k+1}} \bar{\psi}_{v}^{\alpha\beta} (\xi) \, d\xi = \frac{r_v T_s}{2} \left[ \hat{i}_{v,k+1|k-1} + \hat{i}_{v,k|k-2} \right] \tag{3.16}
\]

**Corrective flux change given by the current controller**

At time instant \( t_{k-1} \) the converter current \( \hat{i}_{v,k-1} \) is measured and resolved into dc offset, positive and negative sequences \( \hat{i}_{v,ofs,k-1}, \hat{i}_{v,p,k-1}, \hat{i}_{v,n,k-1} \); and the positive and the negative sequences are further resolved into current components in the rotating coordinate systems. Because of the two-sample delay, the obtained converter current components at time instant \( t_{k-1} \) are compared with the reference components from time instant \( t_{k-3} \).
\[
\begin{align*}
\Delta \hat{I}_{q,v,p,k-1}^{\alpha\beta} & = \hat{I}_{q,v,p,ref,k-3}^{\alpha\beta} - \hat{I}_{q,v,p,k-1}^{\alpha\beta} \\
\Delta \hat{I}_{q,v,n,k-1}^{\alpha\beta} & = \hat{I}_{q,v,n,ref,k-3}^{\alpha\beta} - \hat{I}_{q,v,n,k-1}^{\alpha\beta} \\
\Delta \hat{I}_{q,v,ofs,k-1}^{\alpha\beta} & = \hat{I}_{q,v,ofs,ref,k-3}^{\alpha\beta} - \hat{I}_{q,v,ofs,k-1}^{\alpha\beta}
\end{align*}
\tag{3.17}
\]
3 Control Strategies

The current PI controllers will operate as shown below:

\[
\Delta \tilde{\psi}_{reg,k+1|k-1} = \left( k_p \omega I_s \Delta \tilde{I}_{v,ofs,k-1} + \frac{T_s}{\tau_{ofs}} \sum_{m=0}^{k-1} \Delta \tilde{I}_{v,ofs,m} \right)
\]
\[+ \left( k_p \omega \Delta \tilde{I}_{v,p,k-1} + \frac{T_s}{\tau_p} \sum_{m=0}^{k-1} \Delta \tilde{I}_{v,p,m} \right) e^{j\hat{\theta}_{k+1|k-1}}
\]
\[+ \left( k_p \omega \Delta \tilde{I}_{v,n,k-1} + \frac{T_s}{\tau_n} \sum_{m=0}^{k-1} \Delta \tilde{I}_{v,n,m} \right) e^{-j\hat{\theta}_{k+1|k-1}}
\]

(3.18)

This gives the corrective flux change:

\[
\Delta \tilde{\psi}_{reg,k|k-1} = x_n \Delta \tilde{\psi}_{reg,k+1|k-1}
\]

(3.19)

Then the total flux change required for the time interval \( <t_k, t_{k+1} > \) is:

\[
\Delta \tilde{\psi}_{k|k-1} = \Delta \tilde{\psi}_{B,k|k-1} + \Delta \tilde{\psi}_{I,k|k-1}
\]

(3.20)

where

\[
\Delta \tilde{\psi}_{I,k|k-1} = \Delta \tilde{\psi}_{IR,k|k-1} + \Delta \tilde{\psi}_{Iref,k|k-1} + \Delta \tilde{\psi}_{Ireg,k|k-1}
\]

(3.21)

3.1.3 Flux Modulation

The modulation scheme takes the space vector of the converter flux change \( \Delta \tilde{\psi}_{k|k-1} \) as the input reference. The switching instants in the sampling interval \( <t_k, t_{k+1} > \) that produce this desired change of the flux will be calculated in this section.

The flux change in each phase can be obtained by transforming the flux-change vector into phase quantities according to (3.22):

\[
\Delta \tilde{\psi}_{a,k|k-1} = Re \left\{ \Delta \tilde{\psi}_{k|k-1} \right\}
\]
\[
\Delta \tilde{\psi}_{b,k|k-1} = Re \left\{ \Delta \tilde{\psi}_{k|k-1} e^{-j\frac{2\pi}{3}} \right\}
\]
\[
\Delta \tilde{\psi}_{c,k|k-1} = Re \left\{ \Delta \tilde{\psi}_{k|k-1} e^{j\frac{2\pi}{3}} \right\}
\]

(3.22)
With a certain dc side voltage $u_d$, the flux change in phase $x$ in the sampling interval $< t_k, t_{k+1} >$ is related to the coupling function $K_x$ by (3.23), from which the switching time can be calculated.

$$\Delta \hat{\psi}_{x,k|k-1} = \int_{t_k}^{t_{k+1}} u_d K_x(t) \, dt$$  \hspace{1cm} (3.23)

In the classical PWM modulation each of the three phases in the converter switches once in each sampling interval. Accordingly, all coupling functions are equal, alternating 000 and 111, at the start of each sampling interval. The formulas used to calculate the switching times should be developed respectively for the case switching from 000 to 111 and the case switching from 111 to 000, as shown in Fig. 3.4.

**Switching from 000 $\rightarrow$ 111 in the sampling interval $< t_k, t_{k+1} >$**

In this case the integral contributes to the flux component only from the switching instant to the end of the sampling interval.

$$\Delta \hat{\psi}_{x,k} = \int_{t_{x,k}}^{t_{k+1}} u_d K_x(t) \, dt$$

$$= u_d (t_{k+1} - t_{x,k})$$  \hspace{1cm} (3.24)

The formal solution is

$$t_{x,k} = t_{k+1} - \frac{\Delta \hat{\psi}_{x,k}}{u_d}$$  \hspace{1cm} (3.25)

This is a solution for standard sub-oscillation PWM method, with which the maximum voltage vector that can be realized by the converter is limited to the circle with a radius of $\frac{1}{2}u_d$ as shown in Fig. 3.5.

A well-known method to increase the modulation index, called symmetrical sub-oscillation PWM, is to add a zero-sequence component into the converter reference voltages (e.g., [27]). This method is also applicable in the flux modulation. If all switching actions are displaced by the same amount of time the active voltage pulse remains the same. Therefore
the displacement $\Delta t_0$ of the switching times can be arbitrarily selected, resulting in (3.26):

$$t_{x,k} = t_{k+1} + \Delta t_0 - \frac{\Delta \hat{\psi}_{x,k}}{u_d}$$  \hspace{1cm} (3.26)$$

One option is to choose $\Delta t_0$ such that the midpoint of the active pulse occurs in the middle of the sampling interval, i.e. at $\frac{t_{k+1} + t_{k+1}}{2}$, as shown in Fig. 3.6(a).

Figure 3.4: Flux change during one switching period
3.1 Flux Modulation and Deadbeat Current Control

The active voltage pulse starts at the minimum of the three switching times, which is denoted \( \min(t_{a,k}, t_{b,k}, t_{c,k}) \); and it lasts to the maximum of the switching times, \( \max(t_{a,k}, t_{b,k}, t_{c,k}) \). Then the following can be obtained:

\[
\frac{t_k + t_{k+1}}{2} = t_{k+1} + \Delta t_0 - \frac{\min(\Delta \hat{\psi}_{x,k}) + \max(\Delta \hat{\psi}_{x,k})}{2u_d} \tag{3.27}
\]

Solving for \( t_{k+1} + \Delta t_0 \) yields

\[
t_{k+1} + \Delta t_0 = \frac{t_k + t_{k+1}}{2} + \frac{\min(\Delta \hat{\psi}_{x,k}) + \max(\Delta \hat{\psi}_{x,k})}{2u_d} \tag{3.28}
\]

Finally the switching time formulas are:

\[
t_{x,k} = \frac{t_k + t_{k+1}}{2} + \frac{\min(\Delta \hat{\psi}_{x,k}) + \max(\Delta \hat{\psi}_{x,k}) - 2\Delta \hat{\psi}_{x,k}}{2u_d} \tag{3.29}
\]
Figure 3.6: Modified flux change during one switching period

(a) switching from 000 to 111

(b) switching from 111 to 000
3.1 Flux Modulation and Deadbeat Current Control

Switching from 111 → 000 in the sampling interval \(< t_k, t_{k+1} >\)

In this case the integral contributes to the flux component only from the start of the sampling interval to the switching instant.

\[
\Delta \hat{\psi}_{x,k} = \int_{t_k}^{t_{x,k}} u_d K_x (t) \, dt = u_d (t_{x,k} - t_k)
\]

The formal solution is

\[
t_{x,k} = t_k + \frac{\Delta \hat{\psi}_{x,k}}{u_d}
\] (3.31)

Similarly, all the switching times can be displaced by \(\Delta t_0\) so that the midpoint of the active pulse occurs in the middle of the sampling interval, i.e. at \(\frac{t_k + t_{k+1}}{2}\).

\[
t_{x,k} = t_k + \Delta t_0 + \frac{\Delta \hat{\psi}_{x,k}}{u_d}
\] (3.32)

The active voltage pulse starts at \(\min (t_{a,k}, t_{b,k}, t_{c,k})\) and it lasts to \(\max (t_{a,k}, t_{b,k}, t_{c,k})\), which means:

\[
\frac{t_k + t_{k+1}}{2} = t_k + \Delta t_0 + \frac{\min (\Delta \hat{\psi}_{x,k}) + \max (\Delta \hat{\psi}_{x,k})}{2u_d}
\] (3.33)

Solving for \(t_k + \Delta t_0\) yields

\[
t_k + \Delta t_0 = \frac{t_k + t_{k+1}}{2} - \frac{\min (\Delta \hat{\psi}_{x,k}) + \max (\Delta \hat{\psi}_{x,k})}{2u_d}
\] (3.34)

Then the switching time formulas can be obtained:

\[
t_{x,k} = \frac{t_k + t_{k+1}}{2} - \frac{\min (\Delta \hat{\psi}_{x,k}) + \max (\Delta \hat{\psi}_{x,k}) - 2\Delta \hat{\psi}_{x,k}}{2u_d}
\] (3.35)
Table 3.1: Specifications for the simulation system

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>8VA</td>
</tr>
<tr>
<td>Rated current</td>
<td>0.267 A; rms</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>$10\sqrt{3}$ V; line-to-line, rms</td>
</tr>
<tr>
<td>Line impedance</td>
<td>0; e.g. a strong network; for the step response simulation</td>
</tr>
<tr>
<td></td>
<td>72 mH (0.5pu); for the unsymmetrical load simulation</td>
</tr>
<tr>
<td>Phase reactor</td>
<td>17.9 mH (0.15pu)</td>
</tr>
<tr>
<td>DC side capacitor</td>
<td>345 $\mu$ F (0.2J @ 33.9V)</td>
</tr>
<tr>
<td>DC voltage (controlled)</td>
<td>33.9 V</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>1350 Hz (‘triangular frequency’)</td>
</tr>
</tbody>
</table>

3.1.4 Simulation and Experimental Result

In this section, some results from both computer simulations and the real-time simulator will be presented to verify the validity of the deadbeat current control and the flux modulation system. The computer simulations were carried out by means of the power system simulation software -PSCAD. The system parameters used in PSCAD and in the real-time simulator were identical and are listed in Table 3.1.

Fig. 3.7 and Fig. 3.8 depict the step response of the reactive current, from computer simulations and the real-time simulator respectively. The figures show a successful deadbeat control, where the reactive current follows the reference value with a two-sample delay (0.74ms). It also can be seen that the active current was almost unaffected by the step change in the reactive current. As stated above, the cross-coupling was reduced significantly due to the use of flux modulation.

Fig. 3.9 and 3.10 show the converter flux response to the reactive current step change, from the simulation and the real-time simulator respectively. When the converter is commanded to provide reactive power to the network,
it generates flux with larger magnitude.

The converter response to an unsymmetrical load condition (only phase A and phase B are loaded) has also been investigated. In this case, a relatively weak network is assumed with a line impedance of 72\(mH\)(0.5pu). When the control system detects the negative sequence component of the bus voltage caused by the unsymmetrical load, it commands the converter to produce flux with negative sequence, as shown by the elliptic flux loci in Fig. 3.11 and Fig. 3.12, which are recorded from the simulation and the real-time simulator respectively. In these figures, the circular flux loci under normal operation conditions are also plotted with dashed lines as a comparison. With the help of the voltage source converter, the bus voltage is kept balanced even under extremely unbalanced load conditions, which can be seen from Fig. 3.13 and 3.14.
Figure 3.8: Measured step response of the reactive current

Figure 3.9: Simulated converter flux response to a step change in the reactive current
3.1 Flux Modulation and Deadbeat Current Control

Figure 3.10: Measured converter flux response to a step change in the reactive current

Figure 3.11: Simulated converter flux under normal condition and with unsymmetrical load
3 Control Strategies

Figure 3.12: Measured converter flux under normal condition and with unsymmetrical load

Figure 3.13: Simulated bus voltage with unsymmetrical load and VSC
3.2 Power Control of Voltage Source Converters

As stated above, the purpose of the inner current control loop is to provide fast and accurate converter current control and thus facilitate the converter power flow control. Therefore the outputs from the power control loop (or the outer voltage control loop) shall provide the reference values of the reactive and active current components to the inner control loop. The controllability of positive, negative, and offset components of the converter current makes it possible to control both the positive and negative sequence components of the bus voltage.

Due to the integral relation between the bus voltage and bus flux, the latter is less sensitive to disturbances that might occur in the network. Therefore, it is advantageous to control the bus flux, instead of the bus voltage. The control scheme is depicted in Fig. 3.15.

3.2.1 Bus Flux Control

In the outer control loop, three PI controllers are utilized to control the bus flux. The controller working on the magnitude of the positive sequence com-
component of the bus flux commands the reference value of the positive sequence reactive converter current. The negative sequence d and q components of the reference current are given respectively by the two controllers working on the negative sequence d and q components of the bus flux. The offset components of the reference current are set to zero as they are desired.

3.2.2 DC Voltage Control

Charging and discharging the capacitor involves active power exchange and thus energy exchange between the converter and the grid as indicated by (3.36),

$$\frac{d(W_C)}{dt} = \frac{d(\frac{1}{2} C u_d^2)}{dt} = P_d$$

(3.36)

where $W_C$ is the energy stored in the dc side capacitor, $u_d$ is the dc voltage and $P_d$ is the active power flowing into the dc side of the converter.

If the power loss in the converter bridge is neglected, the active power into
the dc side of the converter equals the power flowing into the converter ac side, which is given by:

$$ P_{ac} = -\frac{3}{2} \omega (\psi^d_p i^q_{v,p} - \psi^q_p i^d_{v,p}) $$  \hspace{1cm} (3.37)  

where $\psi^d_p$ and $\psi^q_p$ are positive sequence dq components of the bus flux, $i^d_{v,p}$ and $i^q_{v,p}$ are the positive sequence components of the converter current, and $\omega$ is the angular frequency of the bus flux. Since the PLL locks on the positive sequence of the bus flux, $\psi^q_p$ is very close to zero so that the active power can be approximated as:

$$ P_{ac} = -\frac{3}{2} \omega \psi^d_p i^q_{v,p} $$  \hspace{1cm} (3.38)  

Combining (3.36) and (3.38) results in

$$ \frac{d}{dt}(W_C) = -\frac{3}{2} \omega \psi^d_p i^q_{v,p} $$  \hspace{1cm} (3.39)  

The linearity between the derivative of $W_C$ and $i^q_{v,p}$ shown in (3.39) suggests that it is advantageous to control the energy stored in the capacitor instead of the dc voltage. In addition, since only a capacitor is connected on the dc side, it is advantageous to introduce a virtual resistor $R_{virt}$ in parallel to the capacitor, as shown in Fig. 3.16, in order to increase the system damping when designing the energy controller. Then (3.39) can be modified into:

$$ \frac{d}{dt}(W_C) + \frac{u^2_p}{R_{virt}} = \frac{d}{dt}(W_C) + \frac{2W_C}{R_{virt}C} = -\frac{3}{2} \omega \psi^d_p i^q_{v,p} $$  \hspace{1cm} (3.40)  

The linear relation in (3.40) is represented by the plant model given in (3.41):

$$ G(s) = \frac{W_C(s)}{-i^q_{v,p}(s)} = \frac{3}{2} \omega \psi^d_p (s + \frac{2}{R_{virt}C}) $$  \hspace{1cm} (3.41)  

\[35\]
According to the IMC (internal model control) design method, in order to make the closed-loop transfer function a first order system, i.e., $T = \frac{1}{1+cTs}$, the controller should have the following form:

$$K = \frac{1}{\frac{3}{2}\omega \psi_p^d \tau_c} (1 + \frac{2}{sR_{virt}C})$$

(3.42)

where $1/\tau_c$ is the cut-off frequency or the bandwidth of the closed-loop system.

This is a PI controller with proportional and integral gains given respectively as:

$$k_p = \frac{1}{\frac{3}{2}\omega \psi_p^d \tau_c} , \quad k_i = \frac{1}{\frac{3}{2}\omega \psi_p^d \tau_c R_{virt}C}$$

(3.43)

### 3.2.3 Limitation of the flux change

With a certain dc side voltage, the flux change vector in $\alpha\beta$ plane during each switching period is confined in a hexagon with the side length of $\frac{2}{3}u_d T_s$, as shown in Fig. 3.17. However, during transients, the reference of the flux change delivered by the inner current control loop might exceed the flux change hexagon, which is usually referred as saturation of the modulation. When saturation occurs, on one hand the integration of the current PI controller should be stopped in order to avoid the wind-up of the integrator; on the other hand, the reference of the flux change should be limited according the instantaneous dc voltage. A limitation method called Minimum Amplitude Error Limit method as proposed in [28] is adapted for limitation of saturated flux modulation reference. By this limitation method, the reference flux change vector exceeding the hexagon is replaced with a vector on the hexagon boundary that is closest to the reference and has the minimum amplitude error, as shown in Fig 3.17.
Figure 3.17: Limitation of the flux change reference
4 Active Power Compensation for Sudden Load Changes

4.1 Introduction

The voltage at the point of common coupling in a weak network is very sensitive to load changes. A sudden change in active load will cause both a phase jump and a magnitude fluctuation in the bus voltage, whereas reactive load changes mainly affect the voltage magnitude. With the addition of energy storage to a StatCom, it is possible to compensate for the active power change as well as providing reactive power support. In this chapter, some effective active power compensation schemes are proposed. Simulations and experimental results verify the compensation schemes by showing that a StatCom with energy storage can significantly reduce phase jumps and magnitude deviations of the bus voltage. Simulation results are also presented showing the benefits of active power compensation to certain applications with phase sensitive loads.

As far as voltage quality is concerned, the focus has been on the magnitude whereas less attention has been paid to the impact of the phase angle jumps that might accompany the voltage magnitude fluctuations caused by faults, sudden active load changes, etc. However, a phase jump in the supply voltage may cause malfunction of certain phase sensitive loads such as ac motors, line commutated converters, etc. For instance, an induction motor will suffer large torque stresses when the supply voltage makes a phase jump. The phase jump in the induction motor (IM) supply voltage causes a fast change in the phase of the rotating stator flux. However, the rotor flux cannot follow the stator flux immediately due to
the inertia and the rotor time constant. Typically it takes approximately 100ms for the rotor flux to catch up with the stator flux (this time depends on the time constant of the rotor). Therefore, during this transient, a large current and a large deviation of the motor electrical torque from its steady state value is inevitable. The torque deviation will in turn cause motor speed fluctuations, which might be harmful to certain industrial processes. The impacts of phase jumps on ac motors and their drives are described in [39] and [40] respectively. Utilization of series voltage injection techniques, e.g., dynamic voltage restorers, to mitigate voltage sags with phase jumps has been studied in [41, 42, 43], which show that keeping the load voltage as the pre-sag condition by injecting required voltage in series can protect the load from both magnitude sags and phase angle jumps.

The voltage sag mitigation techniques investigated by the aforementioned works aim to reduce the impact of voltage sags on some particularly protected loads. This work will instead describe control strategies for a StatCom with capacitor energy storage to reduce the voltage phase jump and magnitude fluctuation at the PCC. Simulations and experimental results will be presented showing the benefits of energy storage and verifying the proposed control strategies. The study is focused on the voltage fluctuations caused by sudden changes in the load connected at the PCC.

### 4.2 Active Power Compensation Schemes

Assume a weak network with a fluctuating active load, which in this work is simulated as a resistive load connected and disconnected occasionally, as shown in Fig. 4.1. A VSC is connected at the same bus where the resistive load is connected. Due to the weakness of the power system, a sudden active load change in the PCC will cause bus voltage magnitude deviations as well as phase jumps, which might be unacceptable and even harmful to certain phase sensitive loads. With the availability of various energy storage technologies, more effort could be made to improve power quality regarding
4.2 Active Power Compensation Schemes

The converter can keep the voltage magnitude deviation within a certain range by reactive power compensation even without energy storage. But before the converter starts to provide reactive power, it must first detect a voltage drop at the connecting point. And then it takes some time for the ac voltage controller to respond, because the ac voltage controller is in an outer control loop. However, when an energy storage device (e.g., a large capacitor bank in this work) is connected on the dc side of the converter, the converter can also provide a certain amount of energy to compensate for the active power change under load disturbances. The active power compensation takes the active load as a feed-forward and can be quite fast because of the deadbeat control scheme used in the inner current control loop. By active power compensation, it is possible to reduce the bus voltage magnitude deviation and the phase jump.

In order for the VSC to compensate for the active load, load power or load current measurement is necessary. Due to the utilization of

Figure 4.1: Model of the system under investigation
deadbeat current control in the converter control system, the outer voltage control loop and the active power compensation should provide the current references to the inner current control loop. In case the active load is 3-phase symmetric, load current measurement is more straightforward (and preferable) than load power measurement. The measured load current is transformed into the dq plane using the angle from the PLL that works on the bus flux and the active current (q component) is taken as the reference for the active power compensation.

As stated above, what causes the bus voltage phase jump and magnitude deviation, especially the phase jump, is the sudden change in the active load. To mitigate this problem, initial compensation after the sudden change is essential whereas the compensation afterwards is dispensable.

### 4.2.1 Compensation Scheme I

The compensation scheme is depicted in Fig. 4.2. A high pass (HP) filter (washout filter) is applied to the measured active load current such that the converter provides full active power support only at the initial stage after the load change and then the load current is handed over to the network gradually. Since the energy that can be provided or absorbed by the capacitor bank is limited, limitations must also be set on the filtered active load current before it is taken as the feed-forward reference active current for the converter.

When the feed-forward control commands active current to the converter, the energy stored in the capacitor bank will change accordingly, which in turn will cause the energy controller to react in a way counteracting the feed-forward control. For example, the feed-forward control commands a positive converter current (flowing out of the converter) when the load is switched on. The converter then starts supplying active power immediately, which results in a drop in the stored energy. As soon as the energy controller detects the energy drop, a negative active converter current is ordered to try to keep the energy at the reference value. It should be noted that the feed-forward control is much faster than the energy controller because of the deadbeat control
4.2 Active Power Compensation Schemes

in the inner current control loop. The conflict between these two controls may be settled in favor of the feed-forward control since active power compensation is desired. The higher priority of the feed-forward control is kept by modifying the energy controller reference. A detailed description of each block is given below.

1) HP Filter

Assume a step change $\Delta i_{Ld}^q$ in the active load at time 0, as shown in Fig. 4.3. By means of the HP filter, the reference active converter current commanded by the feed-forward controller is given by

$$i_{v,p,ref,ff}^q = \Delta i_{Ld}^q e^{-\frac{t}{\tau}}$$

(4.1)
4 Active Power Compensation for Sudden Load Changes

where $\tau$ is the time constant of the HP filter.

A simple way to select the time constant for the HP filter is to set it to a fixed value, which should be the maximum allowed time constant $\tau_{\text{max}}$ under all possible active load conditions. Calculation of this value should then be based on the worst case, i.e., with maximum possible load $\Delta i_{Ld,\text{max}}^q$ and minimum energy $\Delta W_{C,\text{min}}$ that can be provided or absorbed at steady state:

$$\Delta W_{C,\text{min}} = \min \{ (W_{C,\text{steady}} - W_{C,\text{min}}), (W_{C,\text{max}} - W_{C,\text{steady}}) \}$$  (4.2)

The energy required by the feed-forward control can be estimated as:

$$\hat{W}_{ff,\text{max}} = \int_0^\infty \frac{3}{2} \omega \psi_p^d \psi_q^p v_{p,v,p,ref,ff} dt = \frac{3}{2} \omega \psi_p^d \Delta i_{Ld,\text{max}}^q \int_0^\infty e^{-\frac{t}{\tau_{\text{max}}}} dt$$

$$= \frac{3}{2} \omega \psi_p^d \Delta i_{Ld,\text{max}}^q \tau_{\text{max}}$$  (4.3)

Setting $\Delta W_{C,\text{min}} = \hat{W}_{ff,\text{max}}$ yields:

$$\tau_{\text{max}} = \frac{\Delta W_{C,\text{min}}}{\frac{3}{2} \omega \psi_p^d \Delta i_{Ld,\text{max}}^q}$$  (4.4)

2) Limitation on the Feed Forward Current

Recognizing that only when the dc voltage is within the safe operation range the converter can provide or absorb active power, the feed forward control should be modified based on the energy stored on the dc side. A comparator can be employed to set the feed-forward reference to zero when the dc side stored energy is out of the safe operation range.

3) Modification of the Energy Reference

As stated above, a PI energy controller is utilized to control the dc side voltage and thus to control the energy for general purpose Var compensation. In case active power compensation is desired, a relatively large energy variation is inevitable. The reference for the energy controller should be modified as
4.2 Active Power Compensation Schemes

![Diagram of active power compensation schemes]

Figure 4.4: Energy reference modification

shown in (4.5):

$$W_{C, \text{ref}}' = W_{C, \text{ref}} - \hat{W}_{ff}$$

(4.5)

where $\hat{W}_{ff} = \int \frac{3}{2} \omega \psi_d q'_{v, p, \text{ref}, ff} dt$ is the estimated energy that the feed-forward control will take from the converter.

As indicated by (4.5), a mechanism is necessary to bring the energy reference back to its steady state, i.e., to bring $\hat{W}_{ff}$ back to zero at steady state, as shown in Fig. 4.4.

As can be seen, the PI controller used to bring $\hat{W}_{ff}$ back to zero is active only when the feed-forward reference current is within a band of $\pm \epsilon$. Here $\epsilon$ is the threshold value to enable the active power compensation. As long as the active power compensation is in force, the input to this PI controller is zero.

4.2.2 Compensation Scheme II

In the compensation scheme shown in Fig. 4.2, the time constant of the HP filter is a fixed value based on the worst case calculation. In order to fully utilize the energy stored on the dc side and thus to minimize the disturbances introduced by the load change to the grid, the filter constant can be
calculated specifically for each load disturbance as shown in Fig. 4.5. When a sudden change in the active load is detected, the time constant of the feed-forward HP filter is updated based on the actual load and energy condition. For detecting sudden load changes, a HP filter with time constant $\tau_1$ in the range of milliseconds can be employed. Whenever the output from this HP filter exceeds a predefined threshold value, e.g., 0.2 pu, a sample pulse is sent out such that the dc side energy and the load current change at that instant are sampled for calculation of the feed-forward HP filter time constant.

Let the sampled energy and active load current change be $W_{C,S}$ and $\Delta i_{Ld,S}$. The energy that can be provided or absorbed by the capacitor bank is:

$$\Delta W_C = \begin{cases} W_{C,\text{max}} - W_{C,S}, & \text{for a step down change} \\ W_{C,S} - W_{C,\text{min}}, & \text{for a step up change} \end{cases} \quad (4.6)$$
4.3 Simulation and Experimental Result

The energy that the feed-forward control will take can be estimated as:

\[ \dot{W}_{ff} = \int_0^\infty \frac{3}{2} \omega_p \psi_p^d q \psi_p^q \Delta p_{v,p,ref,ff} dt \]

\[ = \frac{3}{2} \omega_p \psi_p^d \Delta i_{Ld,S}^q \int_0^\infty e^{-\frac{t}{\tau}} dt \]

\[ = \frac{3}{2} \omega_p \psi_p^d \Delta i_{Ld,S}^q \tau \]  

(4.7)

Setting \( \Delta W_C = \dot{W}_{ff} \) gives:

\[ \tau = \frac{\Delta W_C}{\frac{3}{2} \omega_p \psi_p^d |\Delta i_{Ld,S}^q|} \]  

(4.8)

4.3 Simulation and Experimental Result

4.3.1 Bus voltage Response to Sudden Load Change

As a general case study, e.g., with no specific phase sensitive load involved, the bus voltage magnitude and phase angle in response to sudden active load changes were investigated both in the simulation software PSCAD and in the real-time simulator.

The main circuit and the control system are as shown in Fig. 4.1 but without any sensitive load connected. The transmission line and the phase reactors are represented by their corresponding impedance; and a large capacitor on the converter dc side is used as the energy storage device. A resistive load is switched on and off occasionally. The three phase bus voltage is measured and its magnitude and phase with respect to the infinite bus are derived. The specifications of the system are listed in Table 4.1. The experimental set up has the same numerical value as the simulation system but in V and W instead of kV and MW.

\(^1\)The specification of dc voltage rating and dc capacitor size in this table is just an example. No optimization has been done in this work.
4 Active Power Compensation for Sudden Load Changes

Table 4.1: Specifications of the Simulation System

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage</td>
<td>17.32 kV; line-line, rms</td>
</tr>
<tr>
<td>Converter rating</td>
<td>8 MVA</td>
</tr>
<tr>
<td>Rated current</td>
<td>0.267kA; rms</td>
</tr>
<tr>
<td>Resistive load</td>
<td>6.4 MW</td>
</tr>
<tr>
<td>Line impedance</td>
<td>84.5 mH (0.7pu)</td>
</tr>
<tr>
<td>Phase reactor</td>
<td>18 mH (0.15pu)</td>
</tr>
<tr>
<td>dc side capacitor</td>
<td>3645 μF</td>
</tr>
<tr>
<td>dc voltage</td>
<td>Maximum: 70.7 kV (5pu)</td>
</tr>
<tr>
<td></td>
<td>Steady state: 63.6 kV (4.5pu)</td>
</tr>
<tr>
<td></td>
<td>Minimum: 33.9 kV (2.4pu)</td>
</tr>
<tr>
<td>dc side energy</td>
<td>Maximum: 9.1MJ, τ = 1.138s</td>
</tr>
<tr>
<td></td>
<td>Steady state: 7.4MJ, τ = 0.921s</td>
</tr>
<tr>
<td></td>
<td>Minimum: 2.1MJ, τ = 0.263s</td>
</tr>
<tr>
<td>VSC switching frequency</td>
<td>1350 HZ</td>
</tr>
</tbody>
</table>

Bus voltage response when the resistive load is switched on

The voltage response was simulated for three conditions: with active and reactive compensation, with only reactive compensation, and without compensation. It should be pointed out that the reactive power compensation referred in this chapter is the result of the bus flux PI controller, rather than a feed-forward compensation like the active power compensation. The results are plotted in Fig. 4.6 and Fig. 4.7. Fig. 4.8 shows the zoomed initial response of the voltage magnitude.

It can be seen that in case no compensation was utilized, the bus voltage dropped permanently with the accompaniment of a phase jump of 32°. With reactive power compensation, the voltage magnitude dropped down by 11.6% and was restored after 70ms. However, with active power compensation added, the magnitude just went down by 4.8% and came back after 10-20ms. More noticeable is the improvement of the phase angle jump. Without any compensation, the phase angle shifted to the new angle almost instantaneously. The reactive power compensation did not help much.
4.3 Simulation and Experimental Result

Figure 4.6: Simulated bus voltage magnitude under load disturbance

Figure 4.7: Simulated bus voltage phase angle under load disturbance

cconcerning the phase jump; the phase angle jumped from 0° to about -42° in 38ms and then fluctuated around the steady state angle (-42°) with a peak amplitude of 10° for 200ms. In the case with active power compensation, the initial jump was only 6° for 7ms and then the angle changed gradually toward the steady state. This gradual change of phase angle is of great significance to phase sensitive loads. For instance, it gives enough time for the rotor flux of an induction motor to catch up with the stator flux and thus large torque and current transients can be avoided. For a load with its own PLL, the smooth transition of the supply voltage phase angle reduces the error.
Figure 4.8: Simulated bus voltage magnitude under load disturbance (zoomed)

Figure 4.9: Measured bus voltage magnitude under load disturbance

in the load PLL that will be much larger without active power compensation.

The experimental results plotted in Fig. 4.9 and Fig. 4.10 show good agreement with the simulation results.
4.3 Simulation and Experimental Result

![Graph showing phase angle vs time for different compensation scenarios.]

**Figure 4.10:** Measured bus voltage phase angle under load disturbance

**Bus voltage response when the resistive load is switched off**

Fig. 4.11 and Fig. 4.12 provide a comparison of the simulated bus voltage response for the three conditions; the initial response of voltage magnitude is zoomed into Fig. 4.13. In case only reactive power compensation was utilized, the bus voltage magnitude fluctuated with a maximum of 21% and was restored after 70ms. Active power compensation reduced the amplitude fluctuation to 1.9% and a period less than 20ms. With only reactive power compensation, the phase angle jumped from -42° to 0° in 36ms and then fluctuated for 300ms around the steady state angle 0° with a maximum amplitude of 18°. The active power compensation again made a smooth transition of the phase angle from -42° to 0° and the initial fluctuation is only 6° for 7ms.

Fig. 4.14 and Fig. 4.15 compare the experimental bus voltage responses for different compensation conditions, which are in good agreement with the simulation results.
4.3.2 Application Cases

Many applications can benefit from active power compensation. As examples, several cases have been simulated in PSCAD. In these cases, phase sensitive loads are connected at the bus where the VSC is connected as shown in Fig. 4.1. The specifications of the main circuit are listed in Table 4.2.

\[^2\text{The specification of dc voltage rating and dc capacitor size in this table is just an example. No optimization has been done in this work.}\]
4.3 Simulation and Experimental Result

Figure 4.13: Simulated bus voltage magnitude under load disturbance (zoomed)

Figure 4.14: Measured bus voltage magnitude under load disturbance
Figure 4.15: Measured bus voltage phase angle under load disturbance

Table 4.2: Specifications of the Simulation System²

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage</td>
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<tr>
<td>Resistive load</td>
<td>5 MW</td>
</tr>
<tr>
<td>Line impedance</td>
<td>60 mH (0.5pu)</td>
</tr>
<tr>
<td>Phase reactor</td>
<td>18 mH (0.15pu)</td>
</tr>
<tr>
<td>dc side capacitor</td>
<td>3645 µF</td>
</tr>
<tr>
<td>dc voltage</td>
<td>Maximum: 70.7 kV (5pu)</td>
</tr>
<tr>
<td></td>
<td>Steady state: 56.6 kV (4pu)</td>
</tr>
<tr>
<td></td>
<td>Minimum: 33.9 kV (2.4pu)</td>
</tr>
<tr>
<td>dc side energy</td>
<td>Maximum: 9.1MJ, $\tau = 1.138s$</td>
</tr>
<tr>
<td></td>
<td>Steady state: 5.8MJ, $\tau = 0.725s$</td>
</tr>
<tr>
<td></td>
<td>Minimum: 2.1MJ, $\tau = 0.263s$</td>
</tr>
<tr>
<td>VSC switching frequency</td>
<td>1350 HZ</td>
</tr>
</tbody>
</table>
4.3 Simulation and Experimental Result

![Simulated Electrical Torque](image)

**Figure 4.16:** IM electrical torque under load disturbance

**Induction motors (1.2MW) as the phase sensitive loads**

As a possible application of active power compensation, the torque of an induction motor (IM) was investigated in PSCAD. Connection and disconnection of the resistive load without active power compensation will certainly cause magnitude deviations and phase jumps in the bus voltage as stated above. Simulations show that the electrical torque fluctuation can be reduced significantly by means of active power compensation.

Fig. 4.16 gives a comparison of the response of the electrical torque of the IM when the active load was switched off. The initial response is enlarged into Fig. 4.17 to show clearly the improvement by active power compensation. It can be seen that with active power compensation, the electrical torque fluctuated by 12% for only about 10-20ms and then returned to the normal state. However, without active power compensation, the torque fluctuated by 54% and returned to steady state after 270ms.

**Thyristor converters as phase sensitive loads**

Active power compensation may improve the performance of a thyristor controlled converter under the disturbance of phase jumps. Consider a
thyristor converter connected at the bus feeding a dc motor in a steel mill. Normally, the thyristor converter operates as a rectifier; but under certain circumstances, e.g., the roller with large inertia is breaking, energy will be sent back to the grid resulting in an inverter operation mode. In the inverter mode, a phase jump on the ac side might cause a commutation failure.

In PSCAD, this sensitive load was represented by a thyristor converter with a constant load current (60A) on the dc side and the operation of the thyristor converter was simulated with different firing angles.

Simulations show that due to the active load disturbance, the largest firing angle that could be used in inverter mode without any commutation failure was 149° if no active power compensation was involved. However, with active power compensation, the maximum allowable firing angle could be as large as 162°.

As a curiosity it can also be noted that commutation failure may occur even during rectifier operation. Simulations showed that the smallest firing angle that could be used was 14° without active power compensation but could be reduced to 2° if active power compensation was deployed.

In either operation mode, the active power compensation enables the converter to operate with a power factor closer to unity, which reduces the
reactive power consumption. Moreover, with active power compensation, the thyristor converter can also withstand larger network disturbances.

**VSCs as sensitive loads (800kW)**

A VSC with energy storage can assist other VSCs, which have no energy storage and are connected at the same bus. After the phase jump occurs and before the PLLs of VSCs catch up with the new phase, active power flow between the network and the VSCs is inevitable. The greater the phase jump, the greater the power flow. If the phase jump is large, there exists a risk that the dc voltage of the VSCs will be taken out of the safe operation range. A fast PLL and a fast dc voltage controller will certainly help but at a price of a sensitive control system. The active power compensation can reduce the phase jump significantly and thus protect the VSCs from the phase jump disturbance.

Fig. 4.18 shows the dc side voltage of the load VSC when the resistive load was switched off. Although it is not cost-effective to improve the stability of the VSCs by means of active power compensation, it could possibly be a second benefit drawn from an installed energy storage system.
4.4 Conclusion

Simulations and experiments show that a StatCom with energy storage can significantly reduce the phase jump and magnitude fluctuation of the bus voltage by means of active power compensation and thus improve the reliability of certain phase sensitive applications.
5 Impact of Energy Storage on System Performance under Fault Conditions

5.1 Introduction

Energy storage has drawn increasing attention with the advance of various technologies. Studies in the previous chapter have shown that integration of energy storage into a StatCom can be beneficial for some applications. It will be valuable to investigate the impact of the energy storage on the performance of weak systems under fault conditions. The investigation has been done by studying an example system. The system model was established based on a real system, in which some induction motors driving pumps along a pipeline are fed from a radial transmission line. To facilitate the investigation, some modifications to the real system have been made.

The system under investigation consists of two sources and long radial voltage constrained transmission lines, as shown in Fig. 5.1. Along the lines are 8 lumped loads and 6 induction motors. In addition to the shunt capacitor banks that are connected along with the loads and motors (not shown in the figure), two more 20MVar capacitor banks are installed at bus 5 and bus 10 respectively to compensate for the reactive power consumption in the system. Moreover, 40MVar reactive power is needed to maintain the voltage level at bus 10. This portion of reactive power will be provided either by a capacitor bank (at the absence of StatCom) or by a StatCom and its filter.
All the motors are assumed to have the same polar moment of inertia (J) of 2s. Although the mechanical torque of the motor will reduce with the drop of the motor speed, it is approximated to be constant during the fault for simplicity. This approximation makes the recovery of the motor speed more difficult. The target is to prevent the motors from slipping away and desirably to prevent the motors from slipping out of a certain speed, e.g., 0.95pu, when faults occur in the system.

The critical fault will be the one close to the source, which in this system is the fault at the bus 3. The fault was assumed to occur at the bus 3 end of the line connecting bus 3 and bus 2 in this study. After 103ms of the fault inception, the breaker at the bus 3 end opened and 33ms later the breaker at the bus 2 end opened. The faults applied in the simulations were phase-phase-ground faults.

Since the system is vulnerable to faults close to the sources, more additional reactive power support is necessary to improve the fault ride-through capability of the system and the performance of the motors. As a possibility, the reactive power support can be provided by mechanically switched capacitor banks. However, due to the constraints of the breakers, the capacitor banks can only be switched on with a certain delay with respect to the inception of the faults, usually after the faults are cleared. Alternatively, a StatCom can be installed to provide fast and dynamic power support to the system.
5.1 Introduction

Figure 5.1: System diagram
5 Impact of Energy Storage on System Performance under Fault Conditions

During a fault, the motor terminal voltage is extremely low and the motor is demagnetized. The unbalance between the electrical torque and the mechanical torque decelerates the motor. After the fault is cleared, the motor will start to accelerate if the electrical torque generated is larger than the mechanical torque. In order to produce the required torque, the motor has to be magnetized and thus consumes much more reactive power than under normal condition. If the reactive power support is not sufficient, the motor will keep decelerating until it stops. For this system under the fault condition as specified previously, some motors will run away if no additional reactive power support is available. As indicated by the simulation results shown in Fig. 5.2, this happened to motor 3, 4, 5 and 6, which were far away from the sources.

5.2 Without additional reactive power support

5.3 With two mechanically switched capacitor banks

Additional capacitor banks might be utilized to provide reactive power support under fault conditions. In order to maintain the voltage level at bus 10, a fixed 40MVar capacitor bank should be connected. The faulty line was
disconnected from bus 2 and bus 3 at 103ms and 136ms respectively after the fault inception. The two additional banks A1 and A2 were supposed to be switched on at 135ms and 144ms respectively. They stayed on for 600ms and then were disconnected.

Simulations show that a minimum total capacitor bank rating of 90MVar (2x45MVar) was required for successful motor speed recovery. The motor speeds were depicted in Fig. 5.3(a). Even though the additional capacitor bank could help the system to restore, it created over-voltage problem during the period after the motor speeds got recovered and before the capacitors were switched off. This can be seen from Fig. 5.4(a), which shows the three phase voltages at bus 10. The bus voltage was about 20% higher than the nominal voltage, which is unacceptable for the system.

It is quite straightforward that the more reactive power provided, the faster the motor speeds get restored. However, the over-voltage problem is more severe. The simulation result with 100MVar bank were plotted in Fig. 5.3(b) and 5.4(b). A faster recovery was achieved, but the over-voltage at the connection bus was 8% higher than that with 90MVar capacitor banks.

5.4 With StatCom

Capacitor banks can help the motor to get back to the normal speed after the fault is cleared. However, the capacitor banks are usually switched on after the fault is cleared. A StatCom, in contrast, can provide power support immediately after the fault inception. This power support includes both active and reactive power. Although the StatCom is usually supposed to provide reactive power support, the fault will cause an active power flow from the converter to the network. In the converter control system, a PLL works on the positive sequence component of the ac side bus flux. In case of a fault, there is a phase shift in the bus flux, which generates a difference between the real bus flux phase angle and the phase angle seen by the converter control system before the PLL follows the real angle. As long as the difference exists, the output voltage of the converter is phase advanced.
relative to the real bus voltage and the converter is forced to provide active power resulting in a drop in the dc side voltage. Of course, the active power support is possible only if there is some kind of energy source, e.g., the energy stored in the converter dc side capacitor.

Moreover, by control of the bus voltage through the StatCom, the over voltage problem is avoided.

Simulations have been carried out to study the impact of the con-

\[ \text{Figure 5.3: Motor speed with capacitor banks} \]
The suitable location of the StatCom is bus 10 due to two factors. One is that the critical fault is the one occurs at bus 3; the StatCom should

Figure 5.4: Voltage at the connection bus of capacitor banks

verter rating, dc side capacitor size, and the energy stored in the dc side capacitor on the motor performance. The additional two banks A1 and A2 were replaced by a StatCom, which is connected to bus 10 through a 138kV/33kV transformer and phase reactors with reactance of 0.15pu. Meanwhile, the 40MVar capacitor bank at bus 10 was removed; this portion of reactive power would be provided by the StatCom and its filter capacitors.
keep a certain distance from the fault in order to function effectively. The other reason is that the StatCom should be in the middle of the motor string in order to support all the 6 motors.

During the fault, motor speed keeps dropping due to the unbalance between the developed electrical torque and the load mechanical torque. Meanwhile, the motor is being demagnetized and pushing reactive power into the network. After the fault is cleared, the motor tries to restore the set speed. Since the speed is low, large amount of reactive power is needed for magnetization of the motor and thus indirectly for the speed restoration. To help with the restoration of the motor speed, effort should be made in two aspects, say, reducing the motor speed drop and increasing the reactive power support. Conventionally, the reactive power flow between a StatCom and the network is controlled to maintain the voltage level at the connection point, whereas the active power is controlled to keep a constant dc side voltage. Under such a control strategy, the active power exchange between the converter and the network is determined basically by the dc side voltage. Therefore, the motor speed drop during the fault is mainly determined by the network configuration. However, if an active power compensation mechanism is employed so that the electrical torque developed by the motor can be increased during the fault, the speed drop will then be reduced. This will make the speed restoration afterwards easier. In the section below, the system performance with these two different control strategies will be analyzed.

5.4.1 Converter with reactive power control but without active power compensation

This control strategy was described in section 3.2. Simulations have been carried out in PSCAD to study the impact of the converter rating and dc side capacitor size on the system performance.
Converter rating

With the StatCom at bus 10, a minimum rating of 75MVA was needed for a successful system recovery. Fig. 5.5(a) shows the motor speed with a 75MVA StatCom. Increasing the converter rating from 75MVA to 90MVA made the motor speed recovery faster, which can be seen from Fig. 5.5(b). The voltage at bus 10 was depicted in Fig. 5.6, which shows that no significant over-voltage occurred after the fault was cleared.

Comparing the output power of the StatCom with 75MVA and 90MVA ratings plotted in Fig. 5.7(a) explains why the speed restoration is faster with higher StatCom rating. As mentioned previously, the active power exchange is caused by the phase jump due to the fault occurrence and clearance. With higher converter rating, more reactive power was pushed into the network; hence the bus voltage at the converter connection bus 10 was higher during the fault, as shown in Fig. 5.7(b). Therefore, the same phase jump caused by the fault occurrence took more active power from the converter. During the fault, the motors were being demagnetized, pushing reactive power to the network. The higher converter rating slowed down the demagnetization of the motors. However, the differences were too small to make any big difference in the speed drop of the motors during the fault. The speed of motor 6 was taken as an example in Fig. 5.7(c), since it is the far most motor and the speed restoration situation is most severe. After the fault was cleared, the reactive power provided by the StatCom was larger with higher rating, making the speed restoration faster.

Dc side capacitor size

In previous section, it is assumed that the converter dc side voltage is always at a reasonable level so that the converter can always deliver the required power to the system. Bigger capacitors and higher dc side voltages were employed for those simulations to fulfill this assumption.

As stated above, the converter is forced to provide active power into the network during the fault transients; hence the rating of the dc side
Figure 5.5: Motor speed with StatCom
energy is a concern in this study.

If the converter is not supposed to provide extra active power support to the network, a dc side voltage of 2.4pu might be reasonable. In the flux modulation scheme utilized for the converter control, the reference flux change is limited according to the converter dc voltage. In case the dc voltage drops below a certain level, the saturation in the flux modulation occurs and the converter may not deliver the required power. The threshold value of the dc voltage is not fixed, but depends on the ac side voltage level. During the fault, the ac voltage level becomes lower; therefore the minimum dc voltage without flux modulation saturation is also lower than normal operation condition.

Simulations have been done with a 90MVA StatCom. To compare the performance with different capacitor size, the capacitors are dimensioned in terms of their time constants. The time constant is the time that it takes for the capacitor to be charged to nominal voltage with nominal power, i.e., \( \text{time constant} = \frac{1}{2} \frac{CU_N^2}{P_N} \). Here, \( U_N = 64.7kV \) \( (2.4pu) \) and \( P_N = 90MW \).

Fig. 5.8 shows the speed of motors for dc side capacitors with time constant of 25ms, 55ms, and 100ms respectively. It can be seen that the
Figure 5.7: Performance comparison with 75MVA and 90MVA StatCom
speed of motor 6 could not be restored with 25ms capacitor.

With capacitor of 25ms time constant, the dc voltage dropped down to 1.27pu at 0.22s, 120ms after the fault inception (see Fig. 5.9(a)). The signal monitoring the saturation of the flux modulation is plotted in Fig. 5.10, showing that for a 25ms capacitor, the flux saturation occurred during the time period from 0.158s to 0.249s, whereas no saturation occurred for 100ms case except for the very short period (0.207s-0.209s) immediately after the fault was cleared. The saturation is also reflected in the power output from the converter. From 0.158s, the active and reactive power output were both reduced compared to the simulation result with 100ms capacitor (see Fig. 5.9(b) and 5.9(c)), resulting in a steeper speed drop. Although the saturation ended at 0.249s, the output power was still low because of the low ac side voltage as indicated by the bus flux level in Fig. 5.9(d). The speed kept dropping steeply until 0.35s when the ac voltage catches up with the voltage level of 100ms case. At this time, the dc voltage had reached a level of 2.7pu. The fast rise of the dc voltage was due to the phase jump created by the fault clearance. Even though the converter could provide as much power as the 100ms case, the magnetization of the motor at lower speed consumed much more reactive power, which was beyond the capacity of the converter. The motor finally slipped away.

Similar observations can be made from the simulation results with capacitor of 55ms time constant. However, the saturation occurred for a shorter period (from 0.198s to 0.22s). The speed also dropped more than the 100ms case, but could still be restored.

Simulations show that increasing the capacitor size further made the speed restoration slightly faster but the improvement was not significant.

5.4.2 Converter Control with Active Power compensation

Studies in Chapter 4 have shown that active power compensation can mitigate phase jump related disturbances in a weak transmission system. Because of the quadratic relation between active and reactive power, the con-
Figure 5.8: Motor speeds with different dc capacitor size
Figure 5.9: Performance comparison with different dc capacitor size
The converter can provide certain amount of active power with a little reduction of reactive power support. It is a particular concern whether the active power compensation can help the extremely weak system under investigation in fault condition. In order to provide active power support, the converter must store certain amount of energy on the dc side. The energy storage devices used in this study are large capacitor banks. The energy can be stored by increasing the size of the dc capacitor or raising the dc side steady state voltage, or by a combination of them.

**Compensation scheme**

The inner control loop utilizes flux modulation and deadbeat current control as stated in section 3.1. In the converter outer control loop, the bus flux control described in section 3.2 is employed here, whereas the energy control (dc voltage control) will be modified into a scheme combining active compensation and energy control.

The phase angle from the PLL of the converter control system is an indicator of phase jumps caused by large active load steps or faults, and hence can be taken as the reference of active power compensation. The compensation scheme is depicted in Fig. 5.11. The proportional feed-forward controller takes the PLL phase angle as an input and gives the feed-forward reference value of the converter active current (positive sequence). This

![Figure 5.10: Occurrence of flux modulation saturation](image-url)
feed-forward reference is then limited through a 'Limitation' block as described in section 4.2.1. The energy reference of the energy controller is then modified through the block 'Energy reference modification' as described in section 4.2.1. The limited feed-forward reference and the reference from the energy controller are then added together providing the reference of the positive sequence active current of the converter. Selection of the proportional gain $K_p$ depends on two factors. One is the energy storage capacity of the dc side capacitor and the other one is the optimal division of the converter output power into the active and reactive power for a certain converter rating. The former is quite straightforward. In steady state, the dc voltage is controlled at an intermediate level between the maximum voltage rating of the capacitor and the minimum voltage ensuring effective converter operation. Therefore the maximum energy that the capacitor can absorb or provide is limited. As for dividing the converter output into active and reactive power, the proper ratio depends on the respective importance of the active and reactive power to the motor speed restoration.

**Simulations and Analysis**

Simulations have been done with a 35MVA StatCom using the above compensation scheme. The dc voltage reference was set to 64.7kV(2.4pu), 97kV(3.6pu), and 120kV(4.5pu) for the minimum, steady state, and
maximum levels. The dc side capacitor had a time constant of 55ms\(^1\). By varying \(K_p\), the active power support was varied. The results reported here are from the simulations with \(K_p=1, 4,\) and \(15\) pu/rad respectively. The motor speeds plotted in Fig. 5.12 show that with the increase of the active power support, the motor speed restoration became faster and easier. In case the active power support was not enough (with \(K_p = 1\)), the speed of motor 4, 5 and 6 could not be restored. This implies that the active power support is much more important than the reactive power to the system recovery under fault condition. This can be explained by analyzing the simulation results.

The reactive power supply is important in the sense that the reactive power can help to keep the motor terminal voltage. The electrical torque developed is proportional to the square of the voltage; and the active power provided by the converter is also proportional to the ac side voltage. However, during the fault, the motors could not absorb more reactive power even there was more reactive power supply from the converter. The reason was that the voltage level increased along the line from bus 3 to the end of the line, thus the reactive power flowed in a reverse direction, from bus 14 to bus 3. All the motors were being demagnetized and pushing reactive power to the network, as shown in Fig. 5.13(a), in which motor 6 was taken as an example with \(K_p=1, 4,\) and \(15\) respectively. Although the reactive power output from the StatCom was 10MVar higher in case \(K_p = 1\) (see Fig. 5.13(b)), this portion of the reactive power was mainly transmitted from bus 10 to bus 9, as shown in Fig. 5.13(c) and 5.13(d). Therefore, the resulted difference in the motor input reactive power and the motor terminal voltage were hardly noticeable in Fig. 5.13(a) and 5.14.

In contrast, active power supply during the fault was critical to the system since the developed electrical torque helped to prevent the motor speed from dropping down. The converter active power outputs for \(K_p=1, 4,\) and \(15\) were plotted in Fig. 5.15(a), which show an increase by about 10MW when \(k_p\) changed from 1 to 15. Increase of the active power support reduced the backward phase jump at the connection bus 10, as

---

\(^1\)The specification of dc voltage rating and dc capacitor size in this study is just an example. No optimization has been done in this work.
Figure 5.12: Motor speeds with different $K_p$.
5 Impact of Energy Storage on System Performance under Fault Conditions

Figure 5.13: Reactive power flow during the fault
shown in Fig. 5.16. Relative to bus 9 and bus 11, the voltage phase angle at bus 10 made a forward move. Therefore, the increased portion of the converter active power output was transmitted to bus 9 and bus 11 (see Fig. 5.15(b) and 5.15(c) ) and was then absorbed by the motors, as shown in Fig. 5.15(d). The increased active power supply to the motor reduced the motor speed drop during the fault by 0.01pu, as can be seen from Fig. 5.17. The speed drop reduction resulted in decreased reactive power demand during the post-fault recovery. This explains why such a low converter rating was sufficient for the speed restoration when proper active power compensation scheme was employed, whereas a minimum of 75MVA was required for a successful restoration when no active power feed-forward control was involved.

When the fault was cleared, there was a forward phase jump at bus 10. The active power compensation scheme took extra active power from the network (see Fig. 5.18(a)). However, this did not reduce the active power supply to the motors. Contrarily, as a consequence of the active power compensation, the forward phase jump at bus 10 was reduced (see Fig. 5.19), resulting in larger amount of active power transmission from bus 9 to bus 10(see Fig. 5.18(b)). Therefore, the active power transmitted from bus 10 to bus 11 was increased with the increase of active power support (see Fig. 5.18(c)), so was the active power supply to the motors (see Fig. 5.18(d), in which motor 6 was taken as an example). The combination of the reduced speed drop during the fault and the increased active power.
Figure 5.15: Active power flow during the fault
Based on the above analysis, the proportional gain $k_p$ should be selected in favor of the active power since active power supply during the fault is much more important and useful for preventing the motor speed drop. Smaller speed drop during the fault and continuing large active power support makes the speed restoration faster and less demanding on the post-fault reactive power supply. However, the limitation imposed on $k_p$ by the capacitor voltage rating still exists. As can be seen from Fig. 5.22, with a
Figure 5.18: Active power flow after the fault is cleared
Figure 5.19: PLL phase angle after the fault is cleared

Figure 5.20: Motor 6 speed after the fault is cleared

Figure 5.21: Reactive power supply to motor 6
5 Impact of Energy Storage on System Performance under Fault Conditions

$k_p$ of 15, the capacitor was working close to its voltage rating limit (4.5pu) and the converter minimum operation voltage limit (2.4pu).

5.5 Conclusion

For a weak system with induction motor loads, a StatCom with certain energy storage capacity will effectively help with the system recovery from faults. Although this incurs extra cost for the increasing dc voltage rating and size of the dc side capacitor, the overall rating of the converter can be reduced by utilization of the proposed active power compensation scheme. In case no active power compensation is employed, a larger StatCom rating together with a sufficiently large dc side capacitor is needed for a successful system recovery.

5.6 Discussion

The conclusion on the impact of the energy storage on system performance is quite promising. However, there are several points that might need more discussion.

Figure 5.22: Converter dc voltage
The investigations were based on the simulations with the specific system configuration, motor model, and fault characteristic. Although it might not be adequate to draw a general conclusion about in what extent the energy storage can help the system, studies do show that energy storage is more helpful to weaker systems or the same system with more severe fault situations.

The system performance depends on some control system parameters in a considerable extent, for example, the PLL speed and the energy controller speed. A slower PLL allows the network to take from or push into the StatCom more active power during transients and thus helps the system more, but at a price of a worse overall control performance. So does a slower energy controller. In this study, the control parameters were kept unchanged for all the simulations in order to get fair comparisons.

The motor control in the simulations switched from constant speed control to constant torque control. Simulations show that the pre-fault torque was slightly bigger with higher converter rating. For example, the pre-fault torque of motor 6 was 0.772pu for a 35MVA converter and 0.801pu for a 75MVA converter, which was 3.76% higher. This made the motor recovery situation with 75MVA converter slightly more severe. However, this difference was too small to have any big influence on the final conclusion.
5 Impact of Energy Storage on System Performance under Fault Conditions
6 Energy Storage for Compensation of Cyclic Loads

6.1 Introduction

A particle accelerator is a typical cyclic load consuming pulsating reactive and active power with varying power factor. Fast magnetization and demagnetization of the main magnets require short rise and fall times of the power during each power cycle, as shown in Fig. 6.1. The pulsating load power will create large fluctuations in the bus voltage at the connection point if there is no external voltage support device connected.

In order to mitigate the voltage fluctuation, fast reactive power compensa-

![Graph showing pulsating load power](image)

**Figure 6.1:** Pulsating load power
tion is required. Studies in [44] have shown that, as a possibility, a Static Var Compensator (SVC) can serve this purpose. The reactive power can be almost fully compensated by the SVC, whereas the pulsating active power will be supplied by the network.

This work investigates the possible use of a StatCom with energy storage to improve the power quality at the point of common coupling where the cyclic load is connected. StatComs are widely used in power systems to provide voltage support by supplying reactive power. When energy storage is integrated into a StatCom on the converter dc side, it is possible to provide also active power support to the network. By doing this, not only the voltage magnitude can be well controlled, but also the voltage phase jump can be reduced significantly.

### 6.2 Load model in PSCAD

The cyclic load simulated in PSCAD is a model of a particle accelerator main magnet supplied from a 12-pulse thyristor converter, as shown in Fig. 6.2. The accelerator consumes cyclic active and reactive power with a period of 2 seconds. Fast magnetizing of the main magnet requires a short rise time of the load current (e.g., 650ms). When the acceleration is finished, the main magnet should be demagnetized quickly, requiring a short fall time of the current (e.g., 550ms). The load current is depicted in Fig 6.3.
6.3 Converter control in general

The control system of the cyclic load implemented in PSCAD is shown in Fig. 6.4. The outer loop controls the load current and gives the reference of the thyristor converter output dc voltage. The inner load voltage control loop controls the converter output voltage and delivers the command of the converter firing angle $\alpha$.

6.3 Converter control in general

The voltage source converter is connected to the PCC via phase reactors, as shown in Fig. 6.5. The control system consists of two loops. The inner loop utilizes deadbeat current control and a flux modulation scheme as proposed
6 Energy Storage for Compensation of Cyclic Loads

in section 3.1. The outputs from the outer control loop provide the reference values of the reactive and active current components to the inner control loop, as described in section 3.2. However, the outer loop consists of not only the flux and energy control (dc voltage control), but also includes the reactive and active power compensation as will be illustrated in the following section.

6.4 Compensation of the cyclic load

6.4.1 Reactive power compensation

As stated above, the converter is controlled by a bus flux controller to provide reactive power to the network in order to maintain the bus voltage level. However, the bus flux PI controller takes action only when bus flux deviations have been detected; and its control speed is limited. On the other hand, the load reactive power keeps changing during each load cycle. Hence, even
6.4 Compensation of the cyclic load

though the bus voltage deviation can be controlled within a small range, the duration of the deviation can be quite long (85% of the load cycle as observed from the simulations). In order to obtain a faster voltage control, the pulsating reactive power can be compensated directly. The measured load reactive power $Q_{Ld}$ can be taken as a feed-forward to command the required current and thus reactive power $Q_v$ from the converter. The reactive power provided by the converter is related to the converter current as shown in 6.1:

$$Q_v = \frac{3}{2} \omega (\psi_p^{d,v,p} \psi_p^{q,v,p})$$

(6.1)

where $\psi_p^d$ and $\psi_p^q$ are positive sequence dq components of the bus flux, $i_v^{d,v,p}$ and $i_v^{q,v,p}$ are the positive sequence components of the converter reactive and active current, and $\omega$ is the angular frequency of the bus flux.

Since the PLL locks on the positive sequence of the bus flux, $\psi_p^q$ is very close to zero such that the converter reactive power can be approximated as:

$$Q_v = \frac{3}{2} \omega \psi_p^{d,v,p}$$

(6.2)

Therefore, to directly compensate for the load reactive power, the required reactive current $i_{v,p,ref,ff}^{d}$, given in 6.3, should be added into the reference of the converter positive sequence reactive current.

$$i_{v,p,ref,ff}^{d} = \frac{2Q_{Ld}}{3\omega \psi_p^{d}}$$

(6.3)

Fig. 6.6 shows the reactive compensation and positive sequence flux magnitude control scheme.

6.4.2 Active power compensation

Although the voltage magnitude disturbance at the PCC is mainly caused by the pulsating reactive power, the active load power also plays a role. In addition to the magnitude disturbance, the pulsating active power also
Figure 6.6: Reactive power compensation and flux control

creates phase jumps in the voltage at the PCC, which might degrade the performance of other loads, especially phase sensitive loads, connected at the same point.

In order to mitigate the disturbances introduced by the pulsating active load, active power compensation can be utilized if energy storage devices are connected on the dc side of the converter. In this study, the energy storage device is supposed to be a large capacitor bank. The pulsating active power will be mainly exchanged between the cyclic load and the converter, while the network only needs to supply the average active power to the load. The active power that flows from the converter to the network is determined approximately by the converter current as 6.4:

\[ P_v = \frac{3}{2} \omega (\psi_p^{d} i_{v,p}^{d} - \psi_p^{q} i_{v,p}^{q}) \]  \hspace{1cm} (6.4)

As stated above, the PLL locks on the positive sequence component of the bus flux. As \( \psi_p^q \) is very close to zero, such that the converter reactive power can be approximated as:

\[ P_v = \frac{3}{2} \omega \psi_p^{d} i_{v,p}^{q} \]  \hspace{1cm} (6.5)

To compensate for the pulsating part of the load active power \( P_{ld} \), the feed-forward converter active current reference is then given as:

\[ i_{v,p,ref,ff}^{q} = \frac{2(P_{ld} - P_{ld,av})}{3\omega \psi_p^{d}} \]  \hspace{1cm} (6.6)
6.5 Simulation results

where \( P_{Ld,av} \) is the average active power of the load.

Since the energy that can be provided or absorbed by the capacitor bank is limited within a certain range, limitations must also be set on this calculated feed-forward reference active current of the converter.

When the feed-forward control commands active current to the converter, the energy stored in the capacitor bank will change accordingly, which in turn will cause the energy controller to react in a way counteracting the feed-forward control. For example, the feed-forward control commands a positive converter current (flowing out of the converter) when the load consumes active power. The converter then starts supplying active power immediately, which results in a drop in the stored energy. As soon as the energy controller detects the energy drop, a negative active converter current is ordered to try to keep the energy at the reference value. It should be noted that the feed-forward control is much faster than the energy controller because of the deadbeat control in the inner current control loop. The conflict between these two controls may be settled in favor of the feed-forward control since active power compensation is desired. The higher priority of the feed-forward control is kept by modifying the energy controller reference. The active power compensation and energy control scheme is depicted in Fig. 6.7 and detailed descriptions of blocks 'Limitation', 'Energy reference modification' and 'PI controller' can be found in section 4.2.1.

The diagram of the investigated system and its control scheme are shown in Fig. 6.5.

6.5 Simulation results

Simulations have been performed in PSCAD to verify the proposed compensation strategy. The simulation system configuration is as shown in the upper part of Fig. 6.5. The specifications of the system are listed in Table 6.1. The converter rating used is 50MVA and the capacitors used for the converter filter provide additional 19MVA reactive power.
Since the power quality at the PCC is of great concern, the bus voltage was measured and the amplitude and the phase angle with respect to the infinite bus were extracted.

To see the impact of the load active and reactive power compensation, the bus voltage magnitude and phase angle were recorded with different simulation conditions: general control without feed-forward active and reactive power compensation, with only reactive power compensation, with both active and reactive power compensation.

Fig. 6.8 shows the bus voltage magnitude during one load cycle under different compensation conditions. From the upper plot it can be seen that even without feed-forward active and reactive power compensation, the bus voltage could be kept within the range of 0.98pu-1.02pu except two spikes that occurred when the load active power changed abruptly. Although the voltage deviation was not very large, the duration was quite long (85% of the load cycle). The bus voltage magnitude was improved when the load reactive power was compensated directly by taking it as a feed-forward to the converter reactive power control, as shown in the figure.

\[ \text{Figure 6.7: Active power compensation and energy control} \]

\[ W_c \text{ (dc side energy)} \]

\[ \text{Average} \]

\[ \frac{2}{3}v_p \]

\[ \text{Limitation} \]

\[ W_{c, \text{ref}} \]

\[ \text{Energy reference modification} \]

\[ W'_{c, \text{ref}} \]

\[ \text{PI controller} \]

\[ i_{v, \text{p, ref, ff}} \]

\[ i'_{v, \text{p, ref, ff}} \]
Table 6.1: Specifications of the Simulation System

<table>
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<tr>
<th>Specification</th>
<th>Value</th>
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<tr>
<td>Transformer primary side voltage</td>
<td>400 kV; line-line, rms</td>
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<tr>
<td>Transformer secondary side voltage</td>
<td>17.32 kV; line-line, rms</td>
</tr>
<tr>
<td>Converter rating</td>
<td>50 MVA</td>
</tr>
<tr>
<td>Filter capacitors</td>
<td>19 MVar</td>
</tr>
<tr>
<td>Lumped line impedance</td>
<td>5.5 mH (0.7pu)</td>
</tr>
<tr>
<td>Phase reactor</td>
<td>2.4 mH (0.15pu)</td>
</tr>
<tr>
<td>dc side capacitor</td>
<td>9376 μF</td>
</tr>
<tr>
<td>dc voltage</td>
<td>Maximum: 66 kV (4.7pu)</td>
</tr>
<tr>
<td></td>
<td>Steady state: 33.9 kV (2.4pu)</td>
</tr>
<tr>
<td></td>
<td>Minimum: 33.9 kV (2.4pu)</td>
</tr>
<tr>
<td>dc side energy</td>
<td>Maximum: 20.4MJ, τ = 0.408s</td>
</tr>
<tr>
<td></td>
<td>Steady state: 5.4MJ, τ = 0.108s</td>
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<tr>
<td></td>
<td>Minimum: 5.4MJ, τ = 0.108s</td>
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<tr>
<td>VSC switching frequency</td>
<td>1350 HZ</td>
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</table>

middle plot. With feed-forward reactive power compensation, the reactive load power was almost completely provided by the StatCom (including the 19MVA filter capacitor reactive power). As shown in Fig. 6.9, the network reactive power supply was almost zero for the whole load power cycle.

Even though the overall voltage magnitude was improved, the reactive power feed-forward control had hardly any impact on the voltage spikes. Moreover, the 2 upper plots in Fig. 6.10 show two phase jumps in the bus voltage. A large phase jump means big disturbance to other loads, especially phase sensitive loads such as ac motors, line commutated converters, etc.

When the converter had energy storage capability and the pulsating load active power was compensated by feed-forward active power control as described above, both the magnitude and the phase angle of the bus voltage were well controlled, as indicated by the lower plots of Fig. 6.8 and Fig. 6.10.

By utilization of load power feed-forward control, the pulsating part of the load active power was almost fully provided by the converter, while
Figure 6.8: Bus voltage magnitude
the network only had to supply the average active power. This can be seen from Fig. 6.11, in which the load power, the power taken from the network and the power taken from the StatCom are plotted. Since the network only had to supply the average load active power, there was almost no phase shift in the bus voltage. Although there were two spikes accompanied by the phase jump occurring when the load active power changed abruptly, the magnitude was kept at a fairly low level of 3.2%. The phase jump was also reduced significantly due to the utilization of the active power compensation, which means reduced disturbance to some phase sensitive loads.

Fig. 6.12 shows the variation of the dc voltage and its reference value during two load cycles.

6.6 Conclusion

Cyclic loads may create severe disturbances in the network. Simulations have shown that a StatCom can provide fast reactive power support and thus can stabilize the bus voltage. Integration of energy storage with a StatCom can further mitigate the voltage magnitude disturbance. Additionally, the bus
Figure 6.10: Bus voltage phase angle
Figure 6.11: Active power during one load cycle

Figure 6.12: Converter dc voltage
voltage phase jump caused by the pulsating load active power can be reduced significantly.

### 6.7 Remark

A similar study has been carried out by Dragan Jovcic and Karsten Kahle [45]. In that study, the measured load power is taken as a feed-forward for ac voltage control, which in turn gives the d component of the converter reference voltage. Meanwhile, the load active power is controlled in an outer loop, delivering the reference dc voltage for the inner dc voltage control loop, which gives the q component of the converter reference voltage. Although a different control approach is utilized, the results are in good agreement with the results obtained in this study.
7 Conclusions and Future Work

7.1 Conclusions

The simulation and experimental results reported in section 3.1.4 show that with the presented flux modulation scheme combined with the deadbeat current control, a good performance of the converter control can be achieved. By measuring the bus flux instead of the bus voltage, the system is less sensitive to the measurement noise and disturbance. By controlling the converter flux instead of the converter voltage, the effect of cross coupling between the active and reactive components is effectively reduced.

Simulations and experiments presented in Chapter 4 show that a StatCom with energy storage can significantly reduce the phase jump and magnitude fluctuation of the bus voltage by means of active power compensation and thus improve the reliability of certain phase sensitive applications.

For a weak system with induction motor loads, a StatCom with certain energy storage capacity will effectively improve the system recovery from faults. Although this incurs extra cost for the increasing dc voltage rating and size of the dc side capacitor, the overall rating of the converter can be reduced by utilization of the proposed active power compensation scheme. In case no active power compensation is employed, a larger StatCom rating together with a sufficiently large dc side capacitor is required for a successful system recovery.

Cyclic loads may create severe disturbances in the network. Simulations have shown that a StatCom can provide fast reactive power support and thus can stabilize the bus voltage. Integration of energy storage
with a StatCom can further mitigate the voltage magnitude disturbance. Additionally, the bus voltage phase jump caused by the pulsating load active power can be reduced significantly.

7.2 Future work

In this project, a flux modulation scheme is utilized in the inner loop. Moreover, the bus flux is controlled instead of the bus voltage. The bus flux is measured by physically integrating the bus voltage. It will be interesting to investigate whether flux control can avoid transformer saturation problems that might occur during transients if the bus voltage is controlled instead. This may be a part of the future work.

The penetration of wind power into power systems has been growing in recent years. The grid code nowadays requires that wind generators should have the capability to ride through faults. It will be valuable to investigate the impact of energy storage on the ride-through capability of wind generators.

The investigations that have been performed by far only use conventional capacitors as energy storage. Control studies regarding other forms of energy storage, such as batteries, super-capacitors, etc., might be included in the future work.

The interface between energy storage and converter dc link should be studied. Large variations of the dc side voltage increases the rating of VSCs, a fact which is not desirable in most applications. In order to keep the dc side voltage at a reasonable and constant level, a certain kind of interface may be necessary. In addition, the protection of the converter dc side and the possibility of isolation between the energy storage and converter dc link might be studied in the future.
References


References


References


## List of Acronyms

<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>CAES</td>
<td>Compressed Air Energy Storage</td>
</tr>
<tr>
<td>DPC</td>
<td>Direct Power Control</td>
</tr>
<tr>
<td>HP</td>
<td>High Pass (filter)</td>
</tr>
<tr>
<td>IM</td>
<td>Induction Machine</td>
</tr>
<tr>
<td>LP</td>
<td>Low Pass (filter)</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Locked Loop</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
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<tr>
<td>SMES</td>
<td>Superconducting Magnetic Energy storage</td>
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<tr>
<td>StatCom</td>
<td>Static synchronous Compensator</td>
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<td>VSC</td>
<td>Voltage Source Converter</td>
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List of Acronyms
### List of Symbols

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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<td>$f_{tri}$</td>
<td>Triangular frequency</td>
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<td>$i_v$</td>
<td>Converter current</td>
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<tr>
<td>$i_{v,p}^d$</td>
<td>d component of positive sequence converter current</td>
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</tr>
<tr>
<td>$i_{v,p}^q$</td>
<td>q component of Load current</td>
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<td>$P_{Ld}$</td>
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