TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

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BENEFITS OF MAIN REACTOR BASED SVC IN UTILITY APPLICATIONS

Master of Science thesis

Examiner: prof. Enrique Acha
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ABSTRACT

OSKARI TÖRHÖNEN: Benefits of Main Reactor based SVC in utility applications
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This thesis focuses on static reactive power compensators in utility applications. The objectives for the thesis are to disclose the benefits of the Main Reactor based Static VAr compensator (SVC) compared to the conventional SVC, to find out the most important factors affecting the feasibility of different compensator technologies and to perform a case study, which illustrates the benefits of the Main Reactor concept.

Static compensators, like SVC and Static synchronous compensator (STATCOM), are used in utility applications to provide voltage control and power oscillation damping and to increase capacity and stability of the network.

Reactive power compensating has a major role in controlling the voltage of the transmission system, especially during fault and transient situations. Additionally, reactive power compensation can be used to reduce losses in the transmission system in a steady state.

Due to STATCOMs modularity and good tolerance for varying network conditions, its competitiveness has improved, compared to SVC. Sometimes conditions in the power system are so harsh that the performance of the traditional SVC is not sufficient enough to meet all the requirements. Main Reactor concept improves the performance of SVC and provides a cost-effective, competitive alternative for STATCOM based solutions. This thesis outlines the technical background for the improved performance of Main Reactor SVC.

Characteristics of the Main Reactor SVC are discussed from the most important aspects for the designing process. The case study presented in this thesis revealed the competitiveness of the Main Reactor SVC under challenging network conditions.

TIIVISTELMÄ

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Tämä diplomityö käsittelee sähkönsiirtoverkoissa käytettäviä staattisia loistehon kompensaattoreita. Työn tavoitteena on tuoda esiin Main Reactor SVC:n (engl. Static VAr Compensator) etuja perinteiseen SVC:hen verrattuna, kartoittaa optimaalisimman kompensointijärjestelmän valintaan vaikuttavia tekijöitä sekä esitellä tapaustutkimus, jossa Main Reactor SVC:n tarjoamia hyötyjä pyritään havainnollistamaan.

Staattisia loistehon kompensaattoreita, kuten SVC ja STATCOM (engl. Static Synchronous Compensator), käytetään sähkönsiirtoverkkojen jännitteen säätöön, stabiilisuuden ja kapasiteetin parantamiseen sekä tehoheilahteluiden vaimennukseen. Siirtoverkkojen jännitteen säädössä loistehon kompensoinnilla on suuri rooli erityisesti häiriö- ja muutostilanteiden yhteydessä. Lisäksi loistehon kompensoinnilla voidaan pienentää siirtoverkossa syntyviä häviöitä jatkuvassa kuormitustilanteessa.

Modulaarisen ja vaihtelevia verkko-olosuhteita hyvin sietävän STATCOM -tekniikan kehittyminen viime vuosina on parantanut sen kilpailukykyä, perinteiseen SVC -tekniikkaan verrattuna. Joskus siirtoverkon olosuhteet voivat olla niin hankalat, ettei perinteisellä SVC:llä pystyisi edes toteuttamaan haluttua ratkaisua. Main Reactor parantaa SVC:n suorituskykyä ja tarjoaa näin kustannustehokkaan, kilpailukykyisen vaihtoehdon STATCOM -järjestelmille. Tässä työssä esitellään mihin Main Reactor SVC:n suorituskyky perustuu ja millaisia mahdollisuuksia Main Reactor -konseptin hyödyntäminen tarjoaa.

Main Reactor SVC:n ominaisuuksia tarkastellaan kompensointijärjestelmän suunnittelua olennaisesti ohjaavien tekijöiden näkökulmasta. Työssä toteutettiin tapaustutkimus, jonka tuloksena Main Reactor SVC osoitti kilpailukykynsä haastavissa verkko-olosuhteissa.

PREFACE

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Tampere, 18.4.2016

Oskari Törhönen

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
FACTS	Flexible AC Transmission Systems
IGBT	Insulated Gate Bipolar Transistor
MMC	Modular Multilevel Converter
MR	Main Reactor
MSC	Mechanically Switched Capacitor
PCC	Point of Common Coupling
POD	Power Oscillation Damping
STATCOM	STATic synchronous COMpensator
SVC	Static Var Compensator
TCR	Thyristor Controlled Reactor
THD	Total Harmonic Distortion
TIF	Telephone Influence Factor
TSC	Thyristor Switched Capacitor
TSR	Thyristor Switched Reactor
VSC	Voltage Sourced Converter
VA	Volt Ampere
VAr	Volt Ampere reactive

δ	Power angle
f	Frequency
B_{Lmax}	Maximum inductive susceptance of the SVC
B_{Cmax}	Maximum capacitive susceptance of the SVC
I	Current
I_{cap}	Capacitive output current of the SVC
I_{ind}	Inductive output current of the SVC
$I_{n,filter}$	Filter current at nth harmonic frequency
$I_{n,TCR}$	TCR current at nth harmonic frequency
$I_{n,trafo}$	Transformer current at nth harmonic frequency
$I_{n,TSC}$	TSC current at nth harmonic frequency
I_Q	Reactive current
P	Real power
Q	Reactive power
Q_{Cmax}	Maximum capacitive output power of the SVC
Q_{Lmax}	Maximum inductive output power of the SVC
V	Voltage
$V_{n,net}$	Network voltage at nth harmonic frequency
V_{ref}	Reference voltage
X	Reactance
X_{slope}	Relative reactance of the SVC regulation slope
$Z_{n,filter}$	Filter impedance at nth harmonic frequency
$Z_{n,MR}$	Main Reactor impedance at nth harmonic frequency
$Z_{n,net}$	Network impedance at nth harmonic frequency
$Z_{n,trafo}$	Transformer impedance at nth harmonic frequency
$Z_{n,TSC}$	TSC impedance at nth harmonic frequency

1. INTRODUCTION

The continuous growing demand for electricity and distributed energy production is creating new challenges for transmission network operators. To avoid building of new transmission lines, it has become mandatory to optimize the use of the existing transmission capacity. On the other hand, the increasing penetration of solar and wind power have brought about a negative effect on power system stability, which makes it harder to utilize the available transmission capacity.

One option to overcome such problems is to use Flexible AC Transmission Systems (FACTS) as a part of the power system. The main aim of the FACTS equipment is to improve the capacity, quality and reliability of the power system by connecting reactive power compensators to key points of transmission lines.

FACTS devices can be divided into series and shunt compensators. Series compensators consist of fixed or controllable capacitor banks connected in series with a transmission line. Series-connected capacitors reduce the inductance of transmission lines and shorten the electrical length of the line. Shunt compensators, such as Static VAr compensator (SVC) and Static synchronous compensator (STATCOM), provide capacitive or inductive reactive power to stabilize the network voltage, during steady-state and faulted situations.

STATCOM-based compensation systems have been capturing some share of the dynamic shunt compensation markets from SVC-based systems. However, SVCs are still dominating as a cost-effective and reliable alternative. The basic configuration of the SVC has remained largely unchanged during the last decades but its development has not stopped entirely. For instance, Main Reactor SVC is a recent innovation, whose purpose is to provide an even more competitive SVC-based alternative to the STATCOM technology.

Normally, STATCOM and SVC are custom-made systems which make the comparison of different solutions difficult, without extensive analysis. The purpose of this thesis is to find out the key parameters which affect the competitiveness of these technologies.

To make the comparison of SVC, Main Reactor SVC and STATCOM reasonable, some background information of these technologies is presented first. Chapters 2 and 3 focus on the purposes, operation principles and main components of the conventional SVC and STATCOM. Chapter 4 presents the innovative Main Reactor solution and its benefits over the conventional SVC.

Chapter 5 compares the feasibility of the SVC, Main Reactor SVC and STATCOM solutions from different vantages. Chapter 6 presents a case study where the objective is to find out the most suitable compensation solution to a particular case.

2. STATIC VAR COMPENSATOR

The SVC system can be used to overcome a range of problems, which occur in the operation of a power system. As seen from the grid, the SVC can be conceptualized as an adjustable susceptance. It improves the performance of a power grid by injecting capacitive or inductive reactive power into the grid, at its point of connection. The name static VAr compensator comes from the fact that there are no rotating components involved in the system, this in contrast to the traditional synchronous condensers [18].

SVCs can be installed either in industrial plants or in transmission systems [18]. The purpose and the functionality of SVC in these applications are slightly different. In this thesis, term SVC refers to utility SVCs for transmission systems. Industrial SVCs are not considered in this thesis.

2.1 Purposes

There are two notable problems that frequently occur in power systems [7, 21]. The first one is the transient stability, which relates to the synchronization of the generators under disturbances on the power system. The second problem is the voltage regulation during varying load and disturbed conditions. SVC is a solution for avoiding these problems.

Reasons for installing SVC depend on the characteristics of the power system. Main purposes of the utility SVC are [6, 7]:

- voltage controlling,
- stability improvement,
- transmission capacity increase,
- power oscillation damping.

It should be noted that, functions of an industrial SVC, such as load balancing, power factor correction or flicker reduction are not considered in this thesis.

SVCs are mostly used for the same purposes as traditional synchronous condensers, but with superior performance. Without the rotating inertia, the response time of SVC is much higher and it is not sensitive to frequency variations in the power system [6]. Also real power losses in SVCs are much smaller compared to synchronous condensers.

2.1.1 Voltage control

The most important feature of SVC is voltage controlling under varying load conditions of the grid [6]. Voltage of the power system is mainly affected by the reactive power flows between sources and loads [1].

Under heavily loaded conditions, the voltage on the transmission systems tends to drop. A further increase in the load will lead to voltage collapse [6]. Generally, when the grid is heavily loaded the load is mostly inductive and consumes reactive power. Therefore SVC can increase the grid's voltage by injecting reactive power into the grid.

Under lightly loaded conditions, the voltage of the system tends to rise due to the capacitance of transmission lines. This phenomenon is called Ferranti effect and it can be neutralized by absorbing reactive power from the grid [3, 6].

Figure 2.1 illustrates theoretical voltage at a load busbar, with and without reactive power compensation. With unlimited compensation, demanded power does not affect to the grid voltage. In practice, the voltage of the grid always depends on the power demand. With compensation, the impact of the power demand to the voltage can be reduced [6].

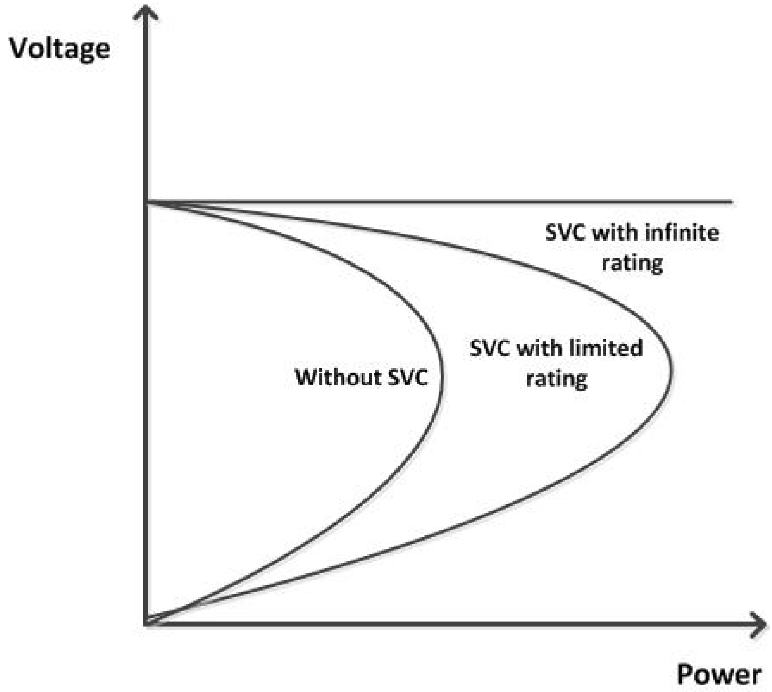

Figure 2.1 *Theoretical voltage at a load busbar as a function of power, with and without SVC*

Power system with a low MVA level of short-circuit faults is called a weak system, which means its voltage is heavily affected by the loading [6]. Especially, weak systems need voltage controlling when heavy loads are switched on or off.

2.1.2 Transmission capacity and stability

The capacity of a transmission system is mainly limited by operating voltage and reactance over the transmission line. Resistance of the transmission system is practically negligible compared to reactance [1]. When considering an ideal two-machine model of a transmission system, real power P transmitted between the machines is given by [19]

$$P = \frac{V_1 V_2}{X} \sin(\delta) , \tag{2.1}$$

where X is the reactance between the machines, V_1 and V_2 are voltages of the machines M_1 and M_2 and power angle δ is the angle difference of the voltage phasor between these machines. Voltage, voltage phasor angle, and reactance between two machines, M_1 and M_2, in an ideal two-machine transmission system are illustrated in figure 2.2.

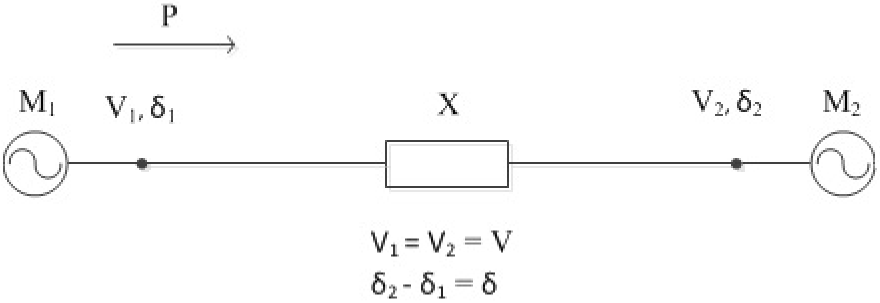

Figure 2.2 *An ideal two-machine model of a transmission system*

If the SVC is connected to the midpoint of the transmission system, the reactance and angle difference between each machine and the SVC are reduced to *X/2* and *δ/2*. Due to this, real power transfer between the machines is given by [19]

$$P = \frac{V^2}{X/2} \sin\left(\frac{\delta}{2}\right) = 2\frac{V^2}{X} \sin(\frac{\delta}{2}) . \tag{2.2}$$

Because the maximum value of the sine function is unity, the ideal real power transfer capacity of the system is doubled by the effect of the SVC. Figure 2.3 represents an ideal two-machine model of a transmission system with a SVC installed to midpoint of the transmission line.

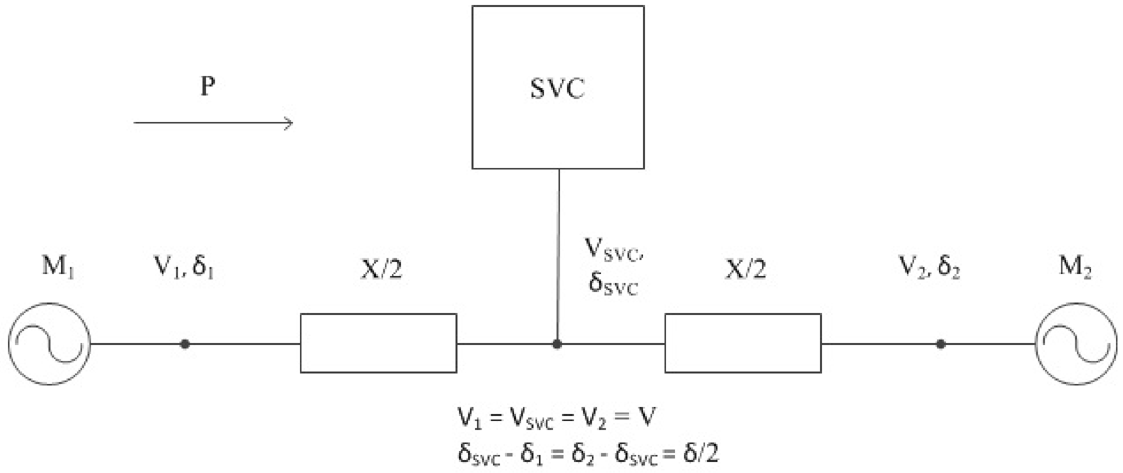

Figure 2.3 *An ideal two-machine model of a transmission system with a SVC*

Increase in the power transfer capacity contributes to the power system's transient stability margin as well. This can be confirmed by the equal-area criterion as illustrated in figure 2.4.

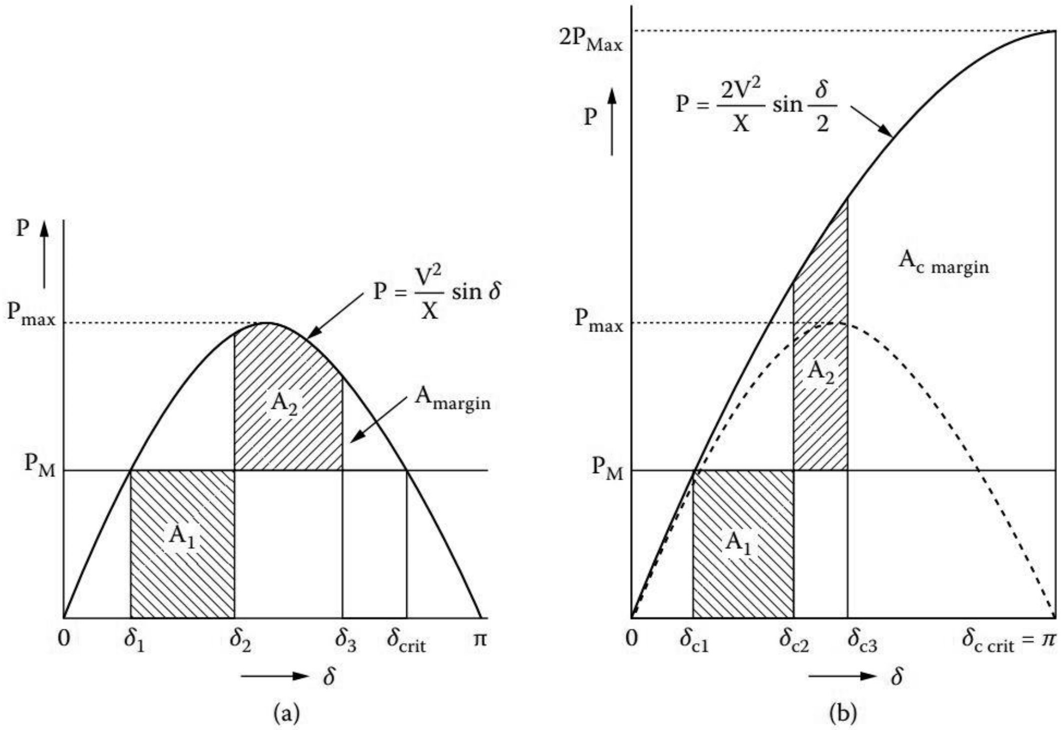

Figure 2.4 *Transient stability margin of two-machine system illustrated by equal-area criterion, without (a) and with (b) compensation [19]*

Increase in the transient stability margin leads to a more stable system. It means that the power system becomes more tolerant to disturbances with the same amount of transmitted power. Alternatively more power can be transmitted with the same stability margin.

2.1.3 Power oscillation damping

Another important feature of the SVC is the ability to attenuate power oscillations in the transmission system. Damping of the power oscillations is important especially in high voltage networks where the voltages are highly dependent on the reactive power flows [9, 15]. Power oscillations are usually caused by sudden changes in power balance under highly loaded operating conditions [9, 18].

Power oscillation damping (POD) in SVC is based on the change in the power angle δ. When δ is increasing, SVC injects reactive power to the systems. This increases the voltage and the real power flow in the transmission system. The increase in the transmitted real power resists acceleration of the generator. Correspondingly, when δ decreases, the reactive power absorbed from the system resists deceleration of the generator [9, 19]. The effect of the POD is illustrated in figure 2.5.

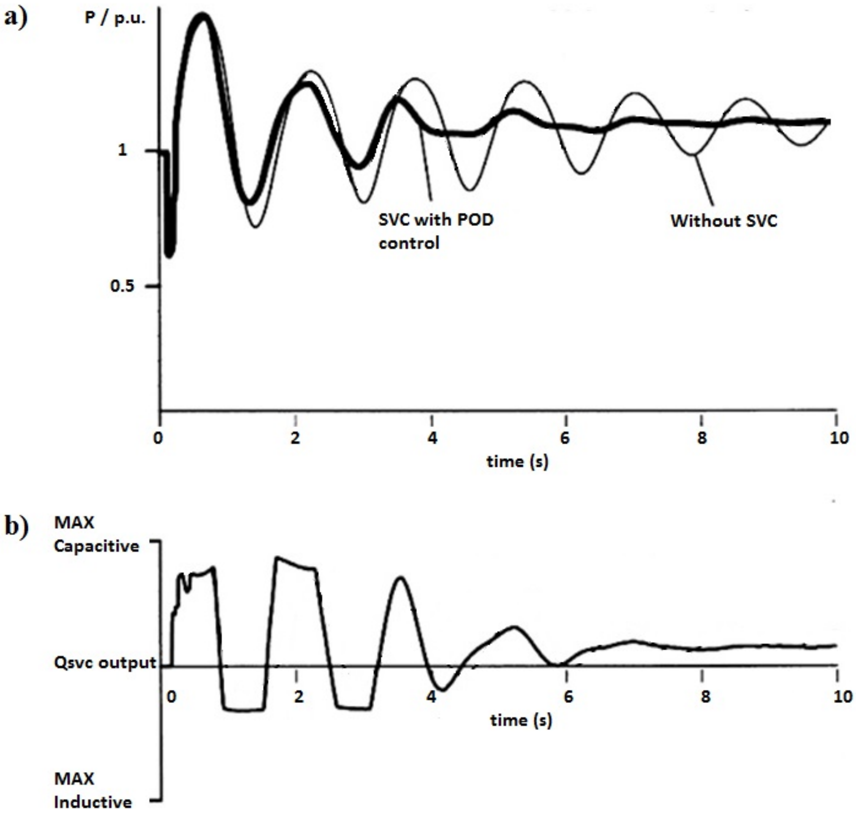

Figure 2.5 a) *Power oscillation damping with and without SVC, b) Reactive power output of SVC during POD-control [19]*

Effectiveness of the POD depends on the rated power of the SVC and the allowed voltage deviation on the transmission system. A SVC with high rated power is able to dampen the real power oscillation effectively, but high damping can lead to reactive power oscillation and voltage fluctuation [15].

It can also be seen in the figure 2.4 that, with the same power flow, the swing angle of the power system with SVC remains much lower compared to the power system without a SVC. This reduces the acceleration of the generators and thus enhances the effectiveness of POD.

2.2 Configuration

The SVC system can be divided into subsystems, which have their own purposes. The branches interact with each other and operation of one branch always influences the others. It should be noted that, the reactive power output of the SVC is subtracted from the capacitive and inductive sources connected. Moreover, transformer between the SVC and grid can be seen as a small inductive power source which also contributes to the reactive power output of the SVC.

Figure 2.6 represents a simplified SVC configuration. Typical configuration includes a step-down transformer, thyristor controlled reactors (TCR), thyristor switched capacitors (TSC) and harmonic filters. In addition to equipment illustrated in the figure 2.6, SVC system encloses control, protection and auxiliary systems. In some cases, auxiliary transformer connected to the SVC busbar is needed to supply power for the auxiliary systems.

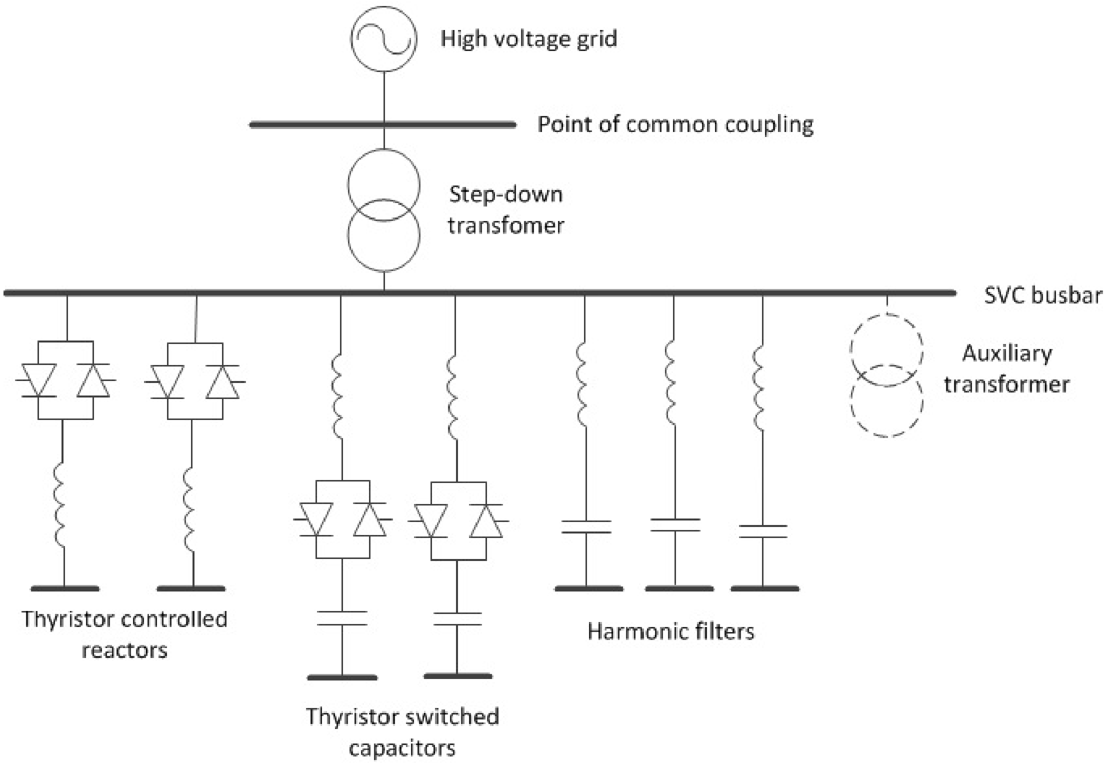

Figure 2.6 *A typical SVC configuration*

Each SVC is a custom-made installation. Amount of different branches and component parameters are designed to meet the customer requirements cost-effectively. In addition, each power system has special characteristics, which have to be taken into account in SVC designing process.

2.2.1 Step-down transformer

Power electronic components in SVC cannot withstand high voltages of the transmission systems. Therefore SVC needs to be connected to the grid through a coupling transformer, which decreases the voltage to a suitable level. Step-down transformer also limits fault currents at the SVC side.

The connection point between the transformer and the grid is called point of common coupling (PCC). Operating voltage of the SVC is normally between 10 kV and 30 kV while the grid voltage can be from 10 kV up to 1200 kV [6]. The coupling transformer is usually wye-delta connected and rating of the transformer depends on the rated power of the SVC.

Construction of the coupling transformer is conventional, but its sizing differs slightly from normal power transformers [12]. Capacitive reactive power increases the voltage on secondary side by means of transformer’s short-circuit impedance and harmonic currents flowing through the SVC transformer are higher compared to conventional transformers. Furthermore, uneven thyristor firing at positive and negative half waves may generate a small DC component on secondary side. Therefore rating of SVC transformer has to be slightly higher compared to the conventional power transformers.

2.2.2 Thyristor controlled reactor

Thyristor controlled reactor is used to provide a continuously controllable power range. TCR adjusts the output during both inductive and capacitive operational ranges of the SVC. Because inductive and capacitive powers cancel each other out, total reactive power output can be controlled by adjusting the amount of inductive power from TCR [17].

A TCR consists of thyristor stacks, often referred as valves, and series-connected reactors [6]. Thyristor valves are made from bidirectional-connected thyristor pairs which allow current controlling on both positive and negative half-cycles of the voltage. The reactor is typically divided into two sections and the thyristor valves are installed between them. This connection limits the fault current through the valve during fault situation in a reactor [18]. In a three-phase system, reactors and thyristor valves of each phase are connected in delta, as shown in figure 2.7 [8, 17].

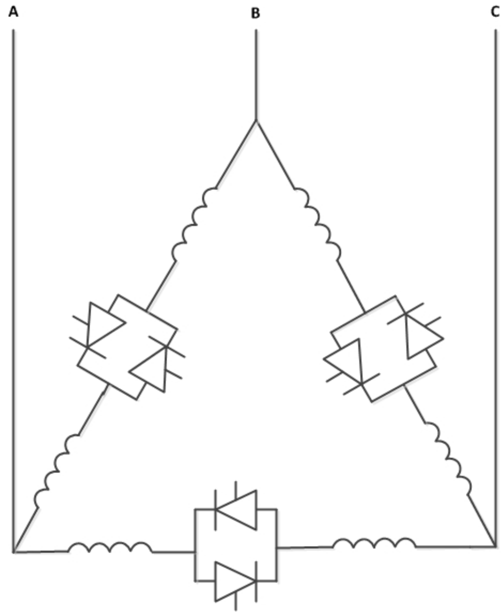

__Figure 2.7__ Delta-connected TCR

Current flowing through the reactor depends on the firing angle of the thyristor valve. The firing angle can be adjusted theoretically between 90 and 180 degrees, but practically the variation can be between 94 and 175 degrees [17].

With firing angle close to 90 degrees the reactive power output of the reactor is the highest. When firing angle is close to 180 degrees, the TCR can be considered as switched off.

TCR operating with firing angle above 90 degrees produces harmonics to the current. Amplitude of different harmonics depends on the firing angle as illustrated in figure 2.8 [17].

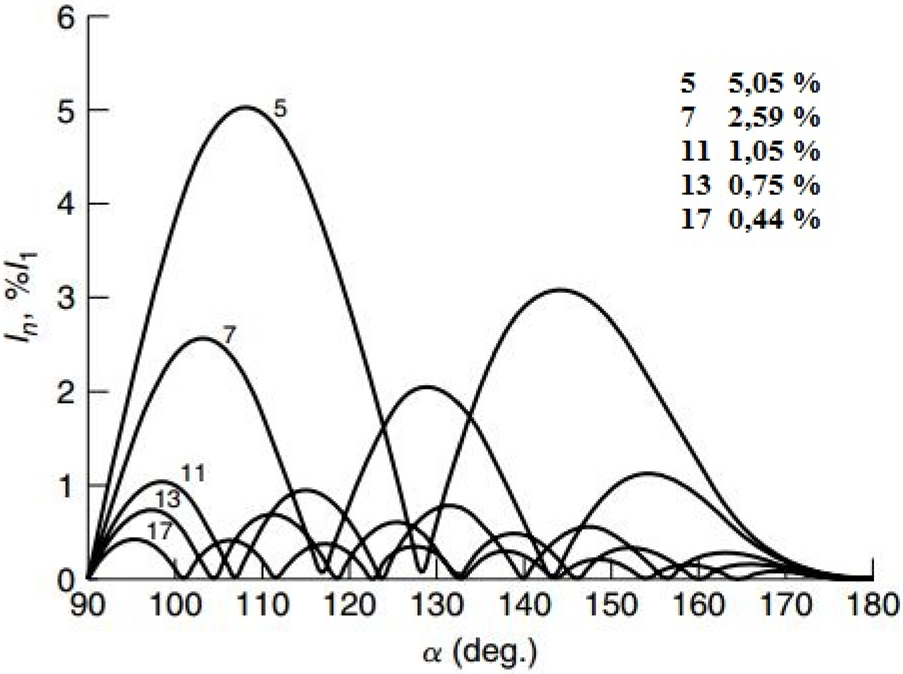

Figure 2.8 *TCR harmonics dependence on the thyristor firing angle [17]*

TCR produces only odd harmonics if the operation of thyristor pairs is symmetrical on positive and negative half cycles. As long as voltages between phases are in balance and control between the phases is symmetric, harmonics divisible by three cannot escape from delta-connected TCR [8].

2.2.3 Thyristor switched capacitor

Capacitive power of the SVC can be provided by fixed capacitors, mechanically switched capacitors (MSC) or TSCs. Switched capacitors can be switched off at inductive or low capacitive operation regions, to minimize the real power losses of the SVC. TSC is often preferred over MSC due to its faster response time.

TSC consists of series connected capacitor banks, thyristor valves and damping reactors. Control of TSC is on-off type and the firing angle off thyristor valves cannot be adjusted as in TCR. Therefore the harmonic generation of TSC is practically zero [6].

Normally multiple TSCs are installed parallel to provide better reliability and step-like reactive power generation [17]. Smaller, independently switched TSC units reduce losses during low capacitive power output of the SVC.

Damping reactors are needed to limit the capacitor charging current after the TSC is switched on. Without damping, the charging current would be theoretically infinite if the TSC switching took place at the worst point-of-wave [17].

Capacitor banks and damping reactors create a resonance circuit which has to be tuned to defined frequency to prevent unwanted interaction with the power system and other branches of the SVC. Three-phase TSC is normally connected in delta, as illustrated in figure 2.9.

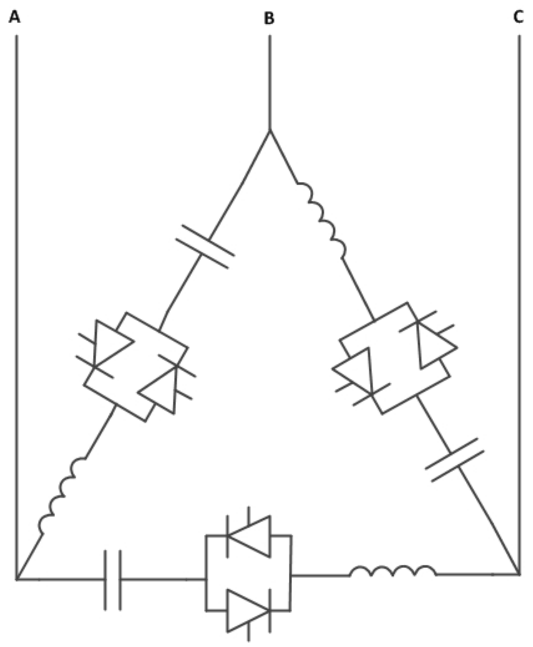

Figure 2.9 *Delta-connected TSC*

Because the capacitive power output of a single TSC is fixed, the total output of the SVC is controlled by TCR. Rated power of a TSC depends on the size of harmonic filters and the total reactive power demand of the SVC. When sizing a TSC, damping reactors must be taken into account since being sources for inductive power these reactors decrease the total capacitive output of TSC [6].

2.2.4 Harmonic filters

Maximum harmonic distortion level at PCC is limited by the standards [11]. Nevertheless, grid operators may have their own, more strict limitations. Due to the harmonic generation mainly by TCR, harmonic filters are often needed to meet harmonic performance requirements.

Commonly used filter types in SVC are represented in figure 2.10. Filters are usually connected to medium voltage side of the transformer to prevent harmonic currents from TCR to enter the transformer.

In addition to filtering, harmonic filters are used to provide fixed capacitive power. Therefore the size of the TSCs can be reduced. In some applications it is possible to produce all capacitive power with the filters without any TSC involved.

On the other hand, during inductive operation of the SVC, fixed reactive power of filters must be covered with a more powerful TCR. Furthermore, filter banks cause permanent real power losses throughout the SVC operation range.

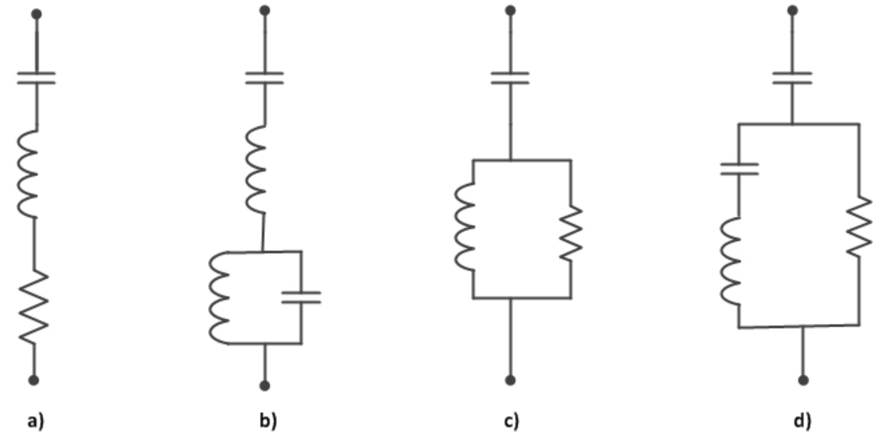

Figure 2.10 *The most common filter types used in SVC: a) single-tuned, b) double-tuned, c) high-pass and d) C-type high-pass*

TCR can also be referred to as a harmonic current source. If the grid has high impedance at a certain harmonic frequency, remarkable harmonic voltage can be observed at this frequency [12]. The function of the harmonic filters is to reduce the impedance at specific frequencies and thus to absorb the corresponding harmonics instead of injecting these harmonics to the transmission system.

The system representation for harmonic rating calculations as seen from the SVC is represented in figure 2.11. Calculation principles for harmonic currents of the main components of the SVC are presented in equations 2.3, 2.4 and 2.5.

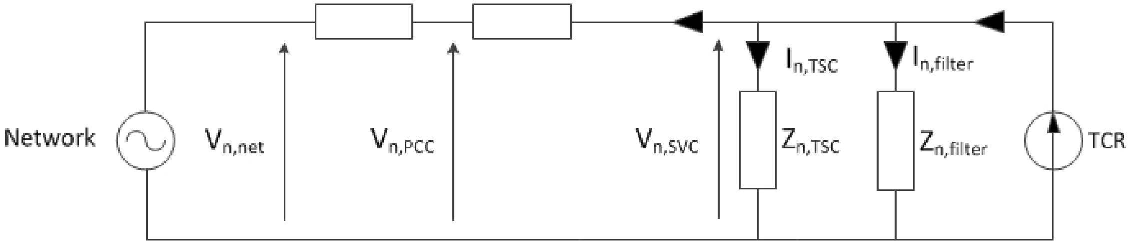

Figure 2.11 *Harmonic currents and impedances of the SVC main components*

$$I_{n,trafo} = \left(1 - \frac{\left[Z_{n,TSC} \parallel \left(Z_{n,trafo} + Z_{n,net}\right)\right] \parallel Z_{n,filter}}{Z_{n,filter}}\right) \cdot \left(\frac{\left(Z_{n,trafo} + Z_{n,net}\right) \parallel Z_{n,TSC}}{Z_{n,trafo} + Z_{n,net}}\right) \cdot I_{n,TCR} + \frac{V_{n,net}}{Z_{n,trafo} + Z_{n,net} + Z_{n,TSC} \parallel Z_{n,filter}} \tag{2.3}$$

$$I_{n,filter} = \left(\frac{\left[Z_{n,TSC} \parallel \left(Z_{n,trafo} + Z_{n,net}\right)\right] \parallel Z_{n,filter}}{Z_{n,filter}}\right) \cdot I_{n,TCR} + \left(\frac{Z_{n,filter} \parallel Z_{n,TSC}}{Z_{n,filter}}\right) \cdot \frac{V_{n,net}}{Z_{n,trafo} + Z_{n,net} + Z_{n,TSC} \parallel Z_{n,filter}} \tag{2.4}$$

$$I_{n,TSC} = \left(1 - \frac{\left[Z_{n,TSC} \parallel \left(Z_{n,trafo} + Z_{n,net}\right)\right] \parallel Z_{n,filter}}{Z_{n,filter}}\right) \cdot \left(\frac{\left(Z_{n,trafo} + Z_{n,net}\right) \parallel Z_{n,TSC}}{Z_{n,TSC}}\right) \cdot I_{n,TCR} + \left(\frac{Z_{n,TSC} \parallel Z_{n,filter}}{Z_{n,TSC}}\right) \cdot \frac{V_{n,net}}{Z_{n,trafo} + Z_{n,net} + Z_{n,TSC} \parallel Z_{n,filter}} \tag{2.5}$$

where,
$I_{n,filter}$ is the current of filter(s) at nth harmonic frequency,
$I_{n,TCR}$ is the current of TCR(s) at nth harmonic frequency,
$I_{n,trafo}$ is the current of transformer nth harmonic frequency,
$I_{n,TSC}$ is the current of TSC(s) at nth harmonic frequency,
$V_{n,net}$ is the voltage of network at nth harmonic frequency,
$Z_{n,filter}$ is the impedance of filter(s) at nth harmonic frequency,
$Z_{n,net}$ is the impedance of network at nth harmonic frequency,
$Z_{n,trafo}$ is the impedance of transformer nth harmonic frequency,
$Z_{n,TSC}$ is the impedance of TSC(s) at nth harmonic frequency.

Harmonic filters are normally slightly detuned from harmonic frequencies to cover manufacturing tolerances and to limit the current through the filter [5]. Above the tuning frequency, reactive power of the filter becomes inductive. To avoid the resonance with the power system in every operation point, filters have to be tuned under the specific harmonic frequency.

2.2.5 Thyristor valve

Voltage rating of a single thyristor disc is normally below 10 kV [18]. Although the connection points of TSC and TCR are on medium voltage side, a series-connection of thyristor discs is needed to limit the voltage stress of thyristors. The series-connection of a several thyristor discs is called a thyristor valve. Figure 2.12 represents a single phase thyristor valve with rating of 23 kV and 4 kA.

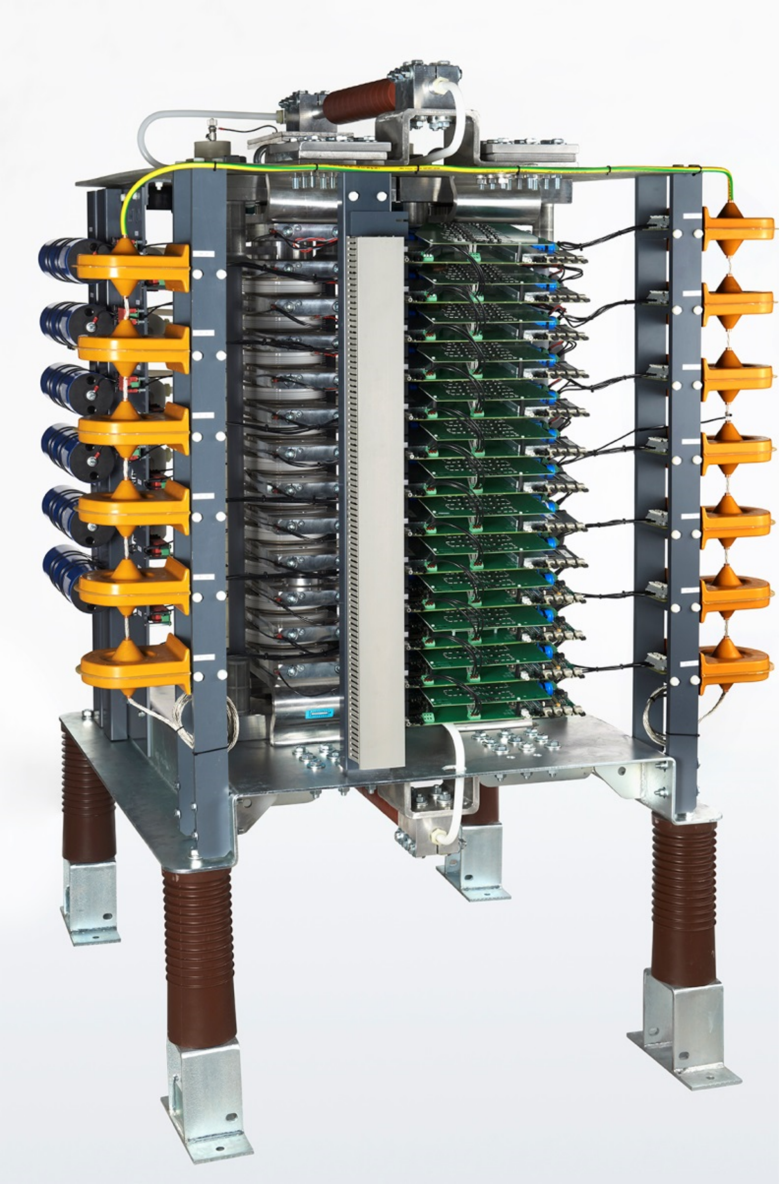

Figure 2.12 *A single phase TCR valve [13]*

The number of thyristor discs needed in a valve depends on the maximum voltage stress over the valve under all possible operation conditions. Compared to TCR valve, maximum voltage stress of the TSC valve is higher due to the residual charge of the capacitor. Residual charge in capacitor and opposite half-wave of the busbar voltage can momentarily produce almost doubled system voltage over a thyristor valve. Therefore the number of thyristor discs in a TSC valve is roughly double compared to a TCR valve with the same voltage rating.

Thyristor valve normally contains a couple of redundant thyristor discs to increase the reliability of the valve. Redundant discs ensure proper operation of the valve and uninterrupted operation of the SVC, even if some of the thyristor discs would fail.

2.2.6 Control and protection systems

The operation of SVC must be fast and reliable under all working conditions, which set high demands for the control and protection systems. The control system must adjust the output of the SVC to correspond the actual need under various conditions. The protection system must be able to protect personnel and the system against excessive loading or fault conditions. It must be able to remove the SVC or parts of it quickly from operation to prevent further damage. In addition, the protection system must operate reliably and it must not trip the SVC during normal operation.

Some objectives [6, 10] for the control system operation are listed below:

- voltage control during normal operation,
- voltage control during disturbances,
- gain control adjustment,
- transient stability control,
- oscillation damping,
- SVC’s internal phase balance control.

SVC control system includes interface between medium voltage thyristor valves and control unit, signal measuring and processing circuits, monitoring system and user interface for graphical display and data entry. In addition to the internal SVC data, control and protection systems need a lot of information about the operation conditions of the transmission system to ensure proper operation of the SVC [10].

2.2.7 Auxiliary system

Auxiliary system comprises of the other systems and components that are essential for proper operation of SVC. Auxiliary system includes AC and DC power sources for control and protection systems, cooling and heating systems [12].

Especially thyristor valves require excessive cooling during operation. Requirements for cooling power can be dozens of kilowatts and sufficient cooling system is essential relative to operation of the whole system. Auxiliary power supply is typically redundant and it is also secured for the most essential loads.

2.3 Operational characteristics

Generally, the output of SVC differs from zero only during disturbances on the power system [10]. If the system is stable and voltage stays in reference value, SVC is in idle state most of its lifespan.

When the operational conditions of the power system change, SVC adjusts its output trying to restore the system back to the normal state. Reactive current output of the SVC on a function of system voltage is illustrated in figure 2.13.

2.3.1 V-I characteristics of SVC

Every SVC has its own V-I characteristics which determines the possible operation states of the SVC. V-I curve presents the output current of the SVC with all permitted PCC voltage values. As can be seen in figure 2.13, SVC allows the system voltage vary slightly in proportion with the output current.

Slope of the V-I curve is a parameter for the SVC control system which determines the sensitivity of the SVC for voltage changes in PCC. Steeper slope leads to smaller change in SVC output current when the voltage at PCC varies.

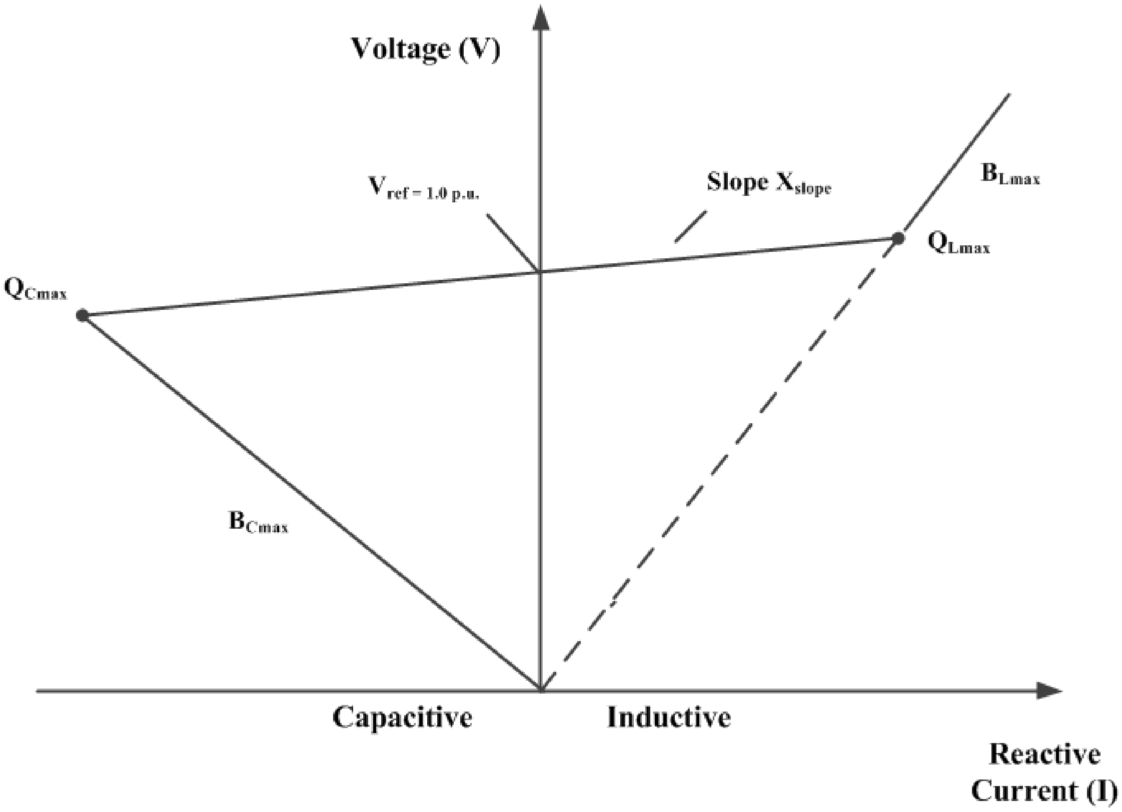

Figure 2.13 *V-I characteristics of a SVC*

Although an ideal SVC would maintain the system voltage unchanged, this slope on the V-I curve actually improves the systems practical functionality in several ways [10]. Firstly, an ideal regulation could lead the SVC to astable state where small variation in power system voltage changes the SVC output from maximum capacitive to maximum inductive, or vice versa. Secondly, the operation range of the SVC can be extended when small voltage droop is allowed. Thirdly, the slope improves the load sharing between other compensating devices in the transmission system.

When SVC is working on its normal regulation range, the system voltage V can be defined by reference voltage V_{ref} from equation 2.6.

$$V = V_{ref} + IX_{Slope}, \tag{2.6}$$

where V_{ref} denotes the system reference voltage, I is the current output of the SVC and X_{slope} is the relative reactance of the regulation slope. Definition of X_{slope} is given by

$$X_{slope} = \frac{\Delta V}{\Delta I}. \tag{2.7}$$

Figure 2.13 reveals that SVC cannot provide its maximum capacitive power if the voltage of the power system decreases too much. After that certain point Q_{Cmax}, the capacitive power output of the SVC decreases with the square of the system voltage and the capacitive output current of the SVC I_{cap} can be defined as follows.

$$I_{cap} = VB_{Cmax} , \tag{2.8}$$

where B_{Cmax} is the maximum capacitive susceptance of the SVC.

When the power system voltage is above its nominal value, SVC is working with inductive output. After point Q_{Lmax}, inductive output current of the SVC I_{ind} is given by

$$I_{ind} = VB_{Lmax} , \tag{2.9}$$

where B_{Lmax} is the maximum inductive susceptance of the SVC.

Maximum capacitive operation is achieved when every TSC is switched on and the firing angle of TCR is close to 180 degrees. Correspondingly, maximum inductive operation is achieved when every TSC is switched off and the firing angle of TCR is close to 90 degrees.

2.3.2 Real power losses

Real power losses compose a considerable part of the SVC life-cycle costs. Cost of the losses can be calculated from loss prices defined by the customer and estimated system losses defined by the SVC supplier.

The amount of total losses depends on the configuration, components and the operational environment of the SVC. As an example, loss-curves of two SVCs with a different design are presented in figures 2.14 and 2.15. Both SVCs have the same operation range +150 / -100 MVAr.

The SVC related to figure 2.14 consists of one TCR, two TSCs and one single-tuned filter. As seen in the figure, TSC switching at 30 MVAr output has a strong impact on the losses. The SVC related to figure 2.15 consists of one TCR, one TSC and three single-tuned filters.

Figures reveal that higher amount of capacitive power generated by the filters increases the losses with inductive and low capacitive output values. However, losses of TSCs are higher, compared to filters, during high capacitive output of the SVC.

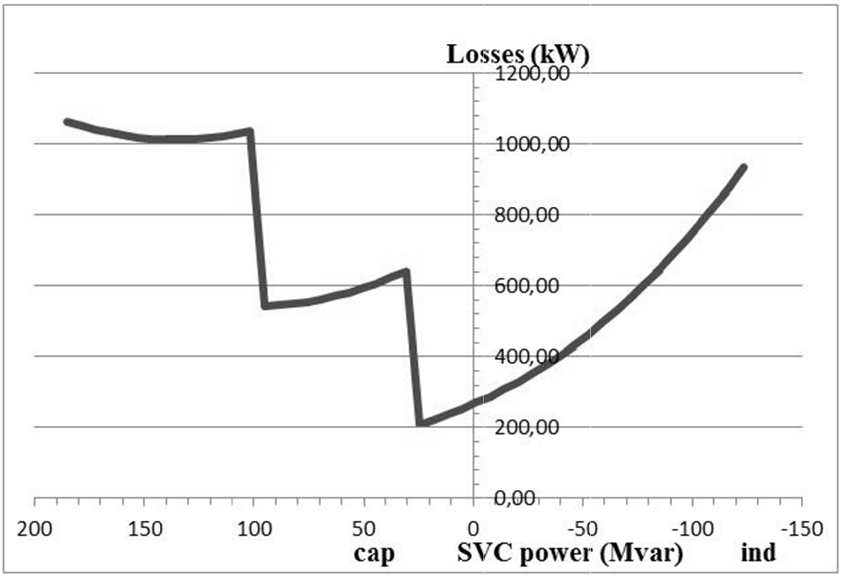

Figure 2.14 *Losses of the SVC with a TCR, 2 TSCs and a filter*

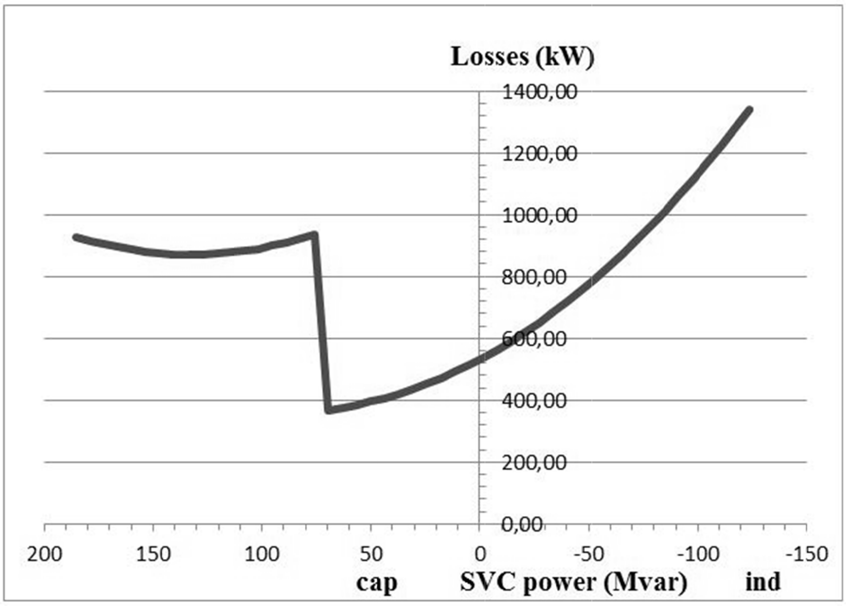

Figure 2.15 *Losses of the SVC with a TCR, a TSC and 3 filters*

Loss optimization is an important part of the SVC design process. Generally, the customer requires an estimate of the SVC losses as a part of the system evaluation. Total cost of the losses can be significant compared to the investment cost of the SVC [14]. Principles for loss evaluation can be found from the standards [12].

3. STATIC SYNCHRONOUS COMPENSATOR

Recent developments in power electronics have paved the way for more advanced techniques for reactive power compensation, which are displacing the bulky reactor units and capacitor banks. One of such novel applications is an inverter-based Static synchronous compensator, commonly abbreviated as STATCOM. While the SVC can be described as a first generation FACTS device, the STATCOM represents the second generation [10].

The STATCOM is used for similar purposes as SVC but its performance as a solid-state voltage source has many great advantages from the operational point of view [4, 10]. Similarly to the SVC, the STATCOM can also be used in distribution, industrial and utility applications. However, the utility applications are highlighted in this thesis. The major benefits of STATCOM compared to SVC are:

- smaller footprint,
- faster response,
- better harmonic performance,
- better low voltage operation,
- better transient stability,
- modular design.

The biggest disadvantage of the STATCOM technology at this point in time, is the higher costs arising from its more complex inverter technology. This technology is still developing and its reliability and power losses still need to be improved further [4].

3.1 Configuration

Basic configuration of a STATCOM consists of a step-down transformer, a coupling reactance, an inverter with insulated-gate bipolar transistors (IGBT) and a DC voltage source [19]. Simplified configuration of a STATCOM is illustrated in figure 3.1.

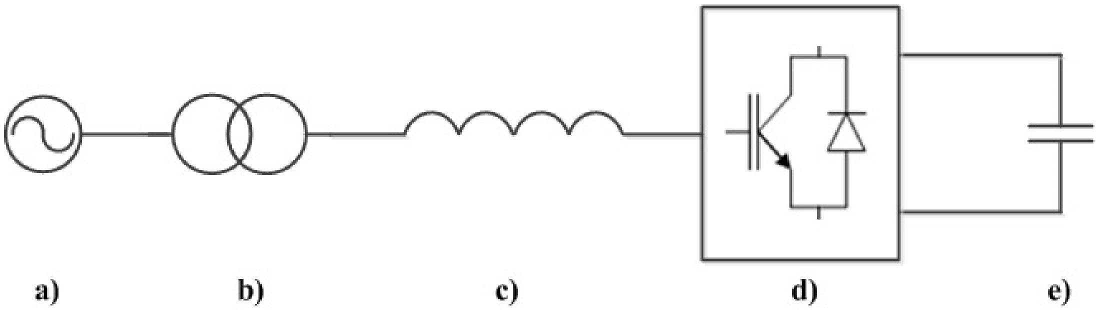

Figure 3.1 *STATCOM configuration: a) grid connection point, b) step-down transformer, e) coupling reactor, d) inverter bridge and e) DC source*

Step-down transformer and its connection to the power system do not differ significantly from SVC. However, the sizing may differ slightly from SVC transformer due to smaller amount of harmonic currents [19].

Voltage over the coupling reactance is controlled by the inverter. The reactive power output of a STATCOM depends on the polarity and magnitude of the reactor voltage. Generally, the coupling reactor is physically smaller than TCR reactors in SVC [17].

Due to smaller harmonic generation of STATCOM, additional harmonic filters are not always required with STATCOM. DC voltage source is normally implemented with DC capacitors [17].

3.2 Modular Multilevel Converter

The inverter type in STATCOM can be classified as Voltage Sourced Converter (VSC). Various different topologies have been discovered for the inverter implementation over time. Currently the most applicable topology is called Modular Multilevel Converter (MMC) [8]. Figure 3.2 represents a simple MMC, especially used in high power applications: three-phase three-level neutral-point clamped (NPC) VSC [18].

The term multilevel refers to converter operation. Multilevel converter utilizes specific switching strategies to generate multilevel output voltage from DC capacitor voltages [18]. Due to the modularity, high output voltages can be achieved by connecting these individually controlled submodules in series. Single submodule for MMC is presented in figure 3.3.

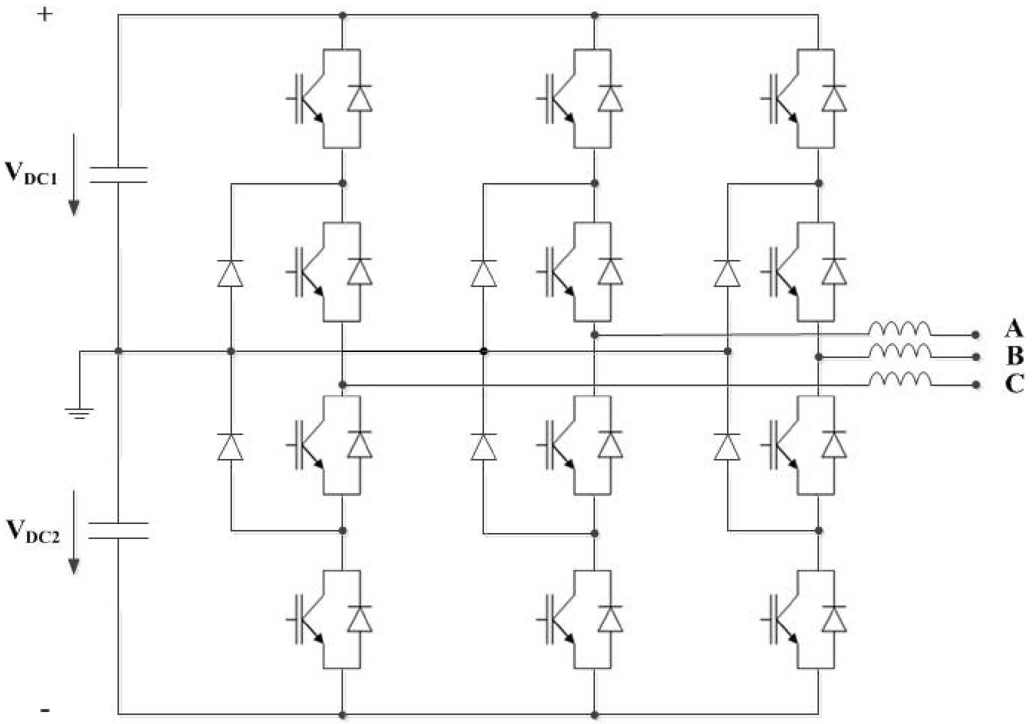

__Figure 3.2__ Three-level three-phase neutral-point-clamped VSC

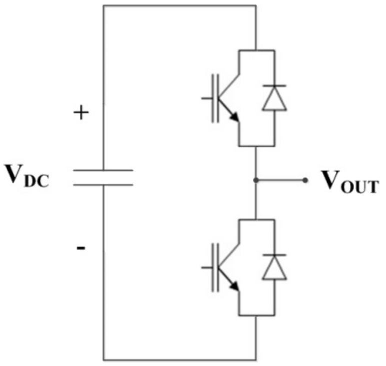

__Figure 3.3__ MMC submodule

A three-level NPC converter produces modified square-wave output voltage with three possible values: positive, negative and zero [18]. Peak-to-peak value of the output voltage is the summed voltage of the capacitors. By adding several converter submodules in series, stepped output voltage with higher amplitude can be achieved.

Figure 3.4 illustrates the simplified series-connection of n submodules per phase for MMC. Output voltage of the MMC becomes more sinusoidal when the amount of submodules increases.

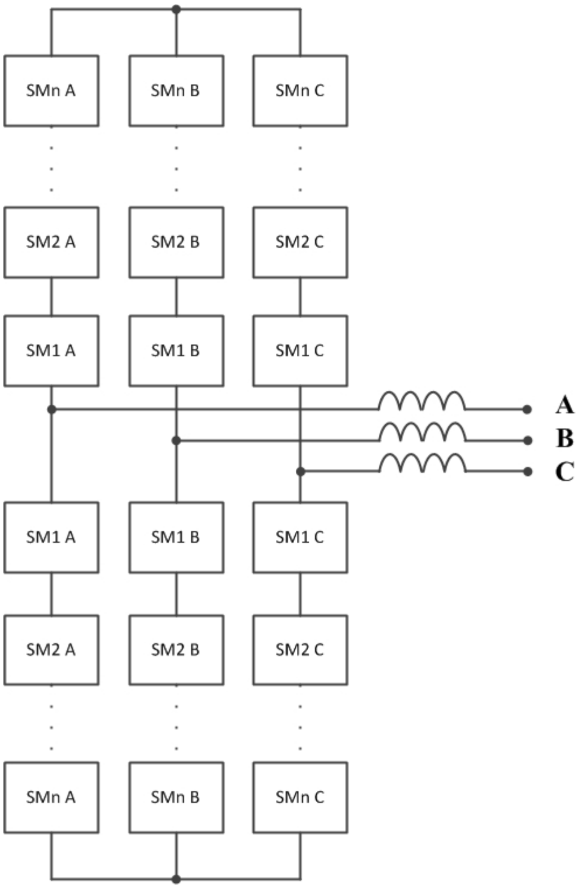

Figure 3.4 *Three phase MMC topology*

Raising the number of submodules increases the probability for converter failure. Reliability of a high-level converter can be increased by including redundant submodules to the converter, meaning that the converter can still be operated even if some of the submodules would fail.

3.3 Operation

STATCOMs fundamental operation differs greatly from SVC. The reactive power of the STATCOM is generated by a power electronic voltage source and therefore the need for large passive components is minimal compared to SVC [18].

From the power system point of view, STATCOM can be seen as a controllable voltage source behind a reactance. Therefore STATCOM can be classified as an active component, while operation principle of SVC is based on passive components. Contrary to SVC, current output of a STATCOM is nearly independent from the power system voltage [17].

3.3.1 Power generation

Reactive power output of a STATCOM can be controlled by varying the converter output voltage. Voltage over the coupling reactance determines the direction and the magnitude of the converter output current and thus the reactive power output [10].

Reactive current I_Q through the coupling reactance is given by [10]

$$I_Q = \frac{V-E}{X}, \tag{3.1}$$

where V denotes the voltage on the transformers medium voltage side, E is the output voltage of the VSC and X is the coupling reactance. The corresponding reactive power Q is given by [10]

$$Q = \frac{1-\frac{E}{V}}{X} V^2. \tag{3.2}$$

When the converter output voltage is higher than the voltage on transformers secondary, the STATCOM injects reactive power to the grid through the transformer. Similarly, if the converter voltage is lower than the transformers secondary voltage, the STATCOM absorbs reactive power from the grid. When the converter output voltage equals transformers secondary voltage, there is no potential difference over the reactance. Without voltage over the reactance, the reactive power output of the STATCOM is zero.

3.3.2 Harmonic generation

Harmonic generation of a STATCOM depends on the converter topology applied. Multilevel converter with sufficient amount of levels is able to produce almost sinusoidal output voltage with very low harmonic content. Figure 3.6 illustrates the voltage generated by an ideal MMC with three and five levels.

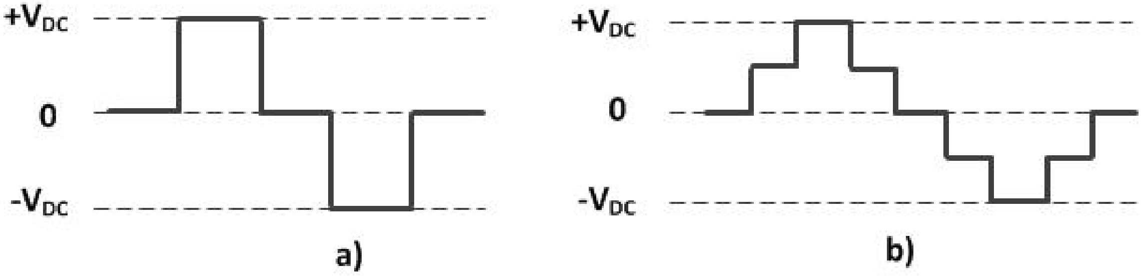

Figure 3.5 *Output voltage of an ideal MMC with a) three and b) five levels*

Switching strategy of MMC can be selected to eliminate the most harmful harmonic frequencies, typically 3rd, 5th and 7th. However, complexity of the STATCOM control system increases with the number of levels, which limits the number of the levels in practical cases.

3.3.3 V-I characteristics of STATCOM

The operation of the STATCOM resembles SVC, but STATCOM is able to maintain reactive current constant during low voltage situations, as long as DC capacitor voltage is sufficient [18]. Hence the reactive power output of a STATCOM decreases in proportion with the voltage. Figure 3.7 illustrates V-I characteristics of the STATCOM.

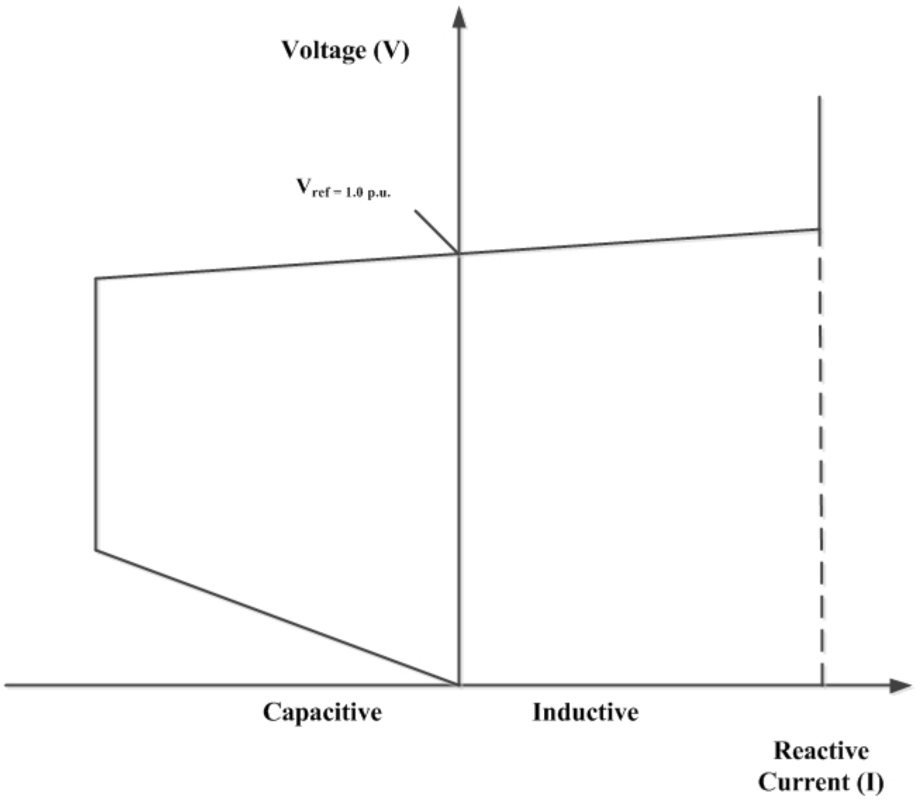

Figure 3.6 *V-I characteristics of the STATCOM*

MVA rating of the VSC is the same for the inductive and capacitive current [17]. Therefore STATCOM has an intrinsically symmetrical operation range.

4. SVC WITH THE MAIN REACTOR

The development of the STATCOM technology has increased its competitiveness compared to the traditional SVC. The increased reliability and capacity of STATCOM based solutions have made it a considerable alternative for SVC. However, SVC has maintained its economical competiveness, and the development of the traditional FACTS systems has not been halted.

The concept of a Main Reactor SVC has been developed in order to enhance the performance of the traditional SVC [20]. The Main Reactor SVC is a patented design, which has already been utilized in several SVC projects around the world with good results. This chapter outlines the configuration, benefits and design of the Main Reactor SVC.

4.1 Configuration

The basic idea of the Main Reactor concept is to increase the reactance between the SVC busbar and the PCC. This is implemented by adding a series-connected reactor after the step-down transformer [20]. The series reactor is named Main Reactor. Figure 4.1 reveals the simplified configuration of the Main Reactor SVC.

Additional series reactor is reasonable because increasing the transformer reactance may be more expensive than a simple air-core reactor [2]. Also optimization of the transformers short-circuit reactance can be done with the Main Reactor, which allows utilizing similar transformers in different projects with the same rated power.

The new arrangement gives two secondary buses, one on each side of the Main Reactor. These new secondary buses are named auxiliary busbar and SVC busbar. Both busbars have different characteristics related to the short-circuit current and voltage fluctuation. Compared to the SVC busbar, the voltage on the auxiliary busbar varies less between different operation conditions. Therefore it provides good connection point for TSCs and an auxiliary transformer [2].

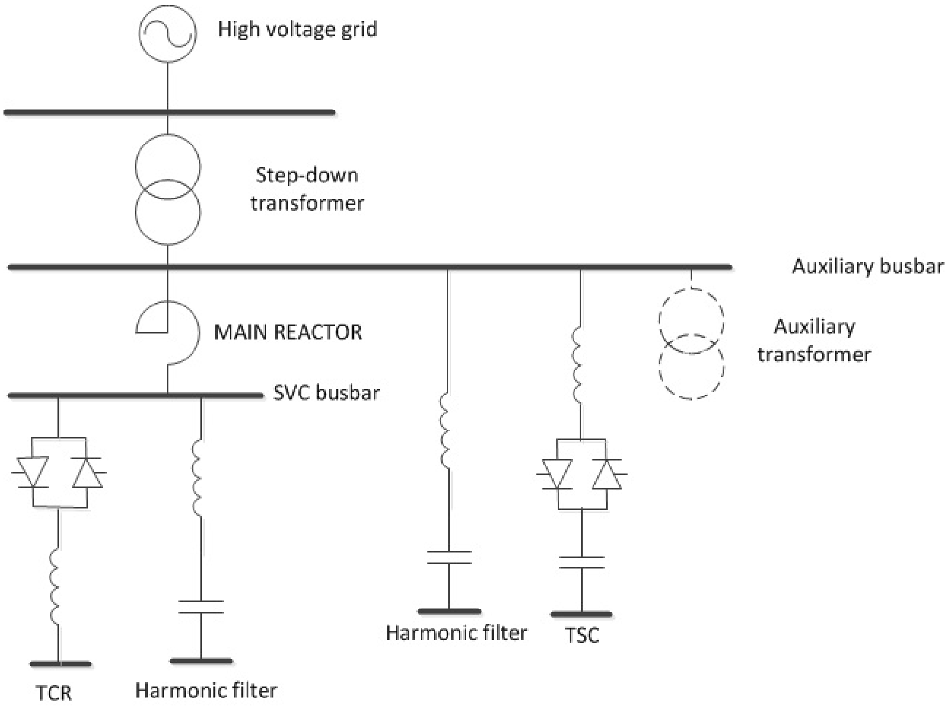

Figure 4.1 *Basic configuration of the SVC with Main Reactor*

The Main Reactor effectively blocks harmonic currents from TCR flowing to the PCC, and from network to the SVC system [2]. Therefore the number of harmonic filters can be reduced compared to conventional SVC. Figure 4.2 represents a simple circuit diagram of impedances of the Main Reactor SVC for harmonic analysis.

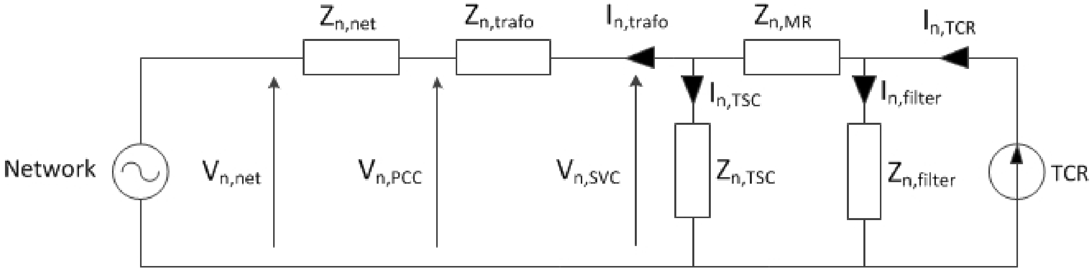

Figure 4.2 *SVC harmonic currents and impedances with the Main Reactor*

4.2 Benefits

The major benefit of the Main Reactor SVC is its superior harmonic performance compared to the traditional implementation. Furthermore, adding a Main Reactor to the SVC design can reduce the number of branches and components required in the SVC. Therefore a smaller footprint and higher reliability, compared to conventional SVC, can be achieved. Table 4.1 summarizes the main features and benefits of the Main Reactor SVC compared to the conventional design.

Table 4.1 *The key features of the Main Reactor SVC*

Features of Main Reactor	**Main Reactor SVC compared to conventional SVC**
Blocking the harmonics from TCR	Better harmonic performance
Blocking the harmonics from PCC to SVC	Better control performance
Smaller short-circuit current in SVC bus	Smaller component rating
Less components	Higher reliability
	Reduced footprint
	Reduced losses
Lower average voltage stress	Increased lifetime of equipment
Design without TSC possible for high capacitive power range	Better step response
Transformer optimization	More flexibility related to the transformer selection

This chapter outlines the benefits of the Main Reactor SVC compared to the traditional SVC design. The information about the benefits of the Main Reactor SVC is based on results gathered from laboratory simulations and experiments from practical implementations.

4.2.1 Harmonic filtering

Impedance of the Main Reactor increases with the frequency. Therefore Main Reactor prevents high order harmonics generated by TCR passing through the transformer to the grid. As operating like a simple low-pass filter, Main Reactor reduces the demand for high order harmonic filters. Based on the figure 4.2, calculation principles for harmonic currents of the Main reactor SVC are presented in equations 4.1, 4.2 and 4.3.

$$\begin{aligned} I_{n,trafo} = {} & \left(1 - \frac{\left[Z_{n,MR} + \left(Z_{n,TSC} \parallel \left(Z_{n,trafo} + Z_{n,net}\right)\right)\right] \parallel Z_{n,filter}}{Z_{n,filter}}\right) \\ & \cdot \left(\frac{\left(Z_{n,trafo} + Z_{n,net}\right) \parallel Z_{n,TSC}}{Z_{n,trafo} + Z_{n,net}}\right) \cdot I_{n,TCR} \\ & + \frac{V_{n,network}}{Z_{n,trafo} + Z_{n,net} + Z_{n,TSC} \parallel \left(Z_{n,filter} + Z_{n,MR}\right)} \end{aligned} \tag{4.1}$$

$$
\begin{aligned}
I_{n,filter} = {} & \left(\frac{\left[Z_{n,MR} + \left(Z_{n,TSC} \parallel \left(Z_{n,trafo} + Z_{n,net} \right) \right) \right] \parallel Z_{n,filter}}{Z_{n,filter}} \right) \\
& \cdot I_{n,TCR} + \left(\frac{Z_{n,TSC} \parallel \left(Z_{n,filter} + Z_{n,MR} \right)}{Z_{n,filter} + Z_{n,MR}} \right) \\
& \cdot \frac{V_{n,network}}{Z_{n,trafo} + Z_{n,net} + Z_{n,TSC} \parallel \left(Z_{n,filter} + Z_{n,MR} \right)}
\end{aligned}
\tag{4.2}
$$

$$
\begin{aligned}
I_{n,TSC} = {} & \left(1 - \frac{\left[Z_{n,MR} + \left(Z_{n,TSC} \parallel \left(Z_{n,trafo} + Z_{n,net} \right) \right) \right] \parallel Z_{n,filter}}{Z_{n,filter}} \right) \\
& \cdot \left(\frac{\left(Z_{n,trafo} + Z_{n,net} \right) \parallel Z_{n,TSC}}{Z_{n,TSC}} \right) \cdot I_{n,TCR} \\
& + \left(\frac{Z_{n,TSC} \parallel \left(Z_{n,filter} + Z_{n,MR} \right)}{Z_{n,TSC}} \right) \\
& \cdot \frac{V_{n,network}}{Z_{n,trafo} + Z_{n,net} + Z_{n,TSC} \parallel \left(Z_{n,filter} + Z_{n,MR} \right)}
\end{aligned}
\tag{4.3}
$$

where,
$I_{n,filter}$ is the current of filter(s) at nth harmonic frequency,
$I_{n,trafo}$ is the current of transformer nth harmonic frequency,
$I_{n,TCR}$ is the current of TCR(s) at nth harmonic frequency,
$I_{n,TSC}$ is the current of TSC(s) at nth harmonic frequency,
$V_{n,net}$ is the voltage of network at nth harmonic frequency,
$Z_{n,filter}$ is the impedance of filter(s) at nth harmonic frequency,
$Z_{n,MR}$ is the impedance of Main Reactor at nth harmonic frequency,
$Z_{n,net}$ is the impedance of network at nth harmonic frequency,
$Z_{n,trafo}$ is the impedance of transformer nth harmonic frequency,
$Z_{n,TSC}$ is the impedance of TSC(s) at nth harmonic frequency.

With the Main Reactor, the number of harmonic filters can be reduced to one or two. Due to the reduction especially in high order harmonics, a typical Main Reactor SVC contains only filters tuned to 5th and 7th harmonic frequency. Figure 4.3 demonstrates the filtering effect of the Main Reactor to 17th harmonic current at PCC.

Main Reactor SVC may contain a harmonic filter on both secondary buses. Purpose of the filter on the SVC busbar is to filter harmonics from TCR to PCC. Harmonic filter on auxiliary busbar allows the filtering off background distortion from external network to the SVC.

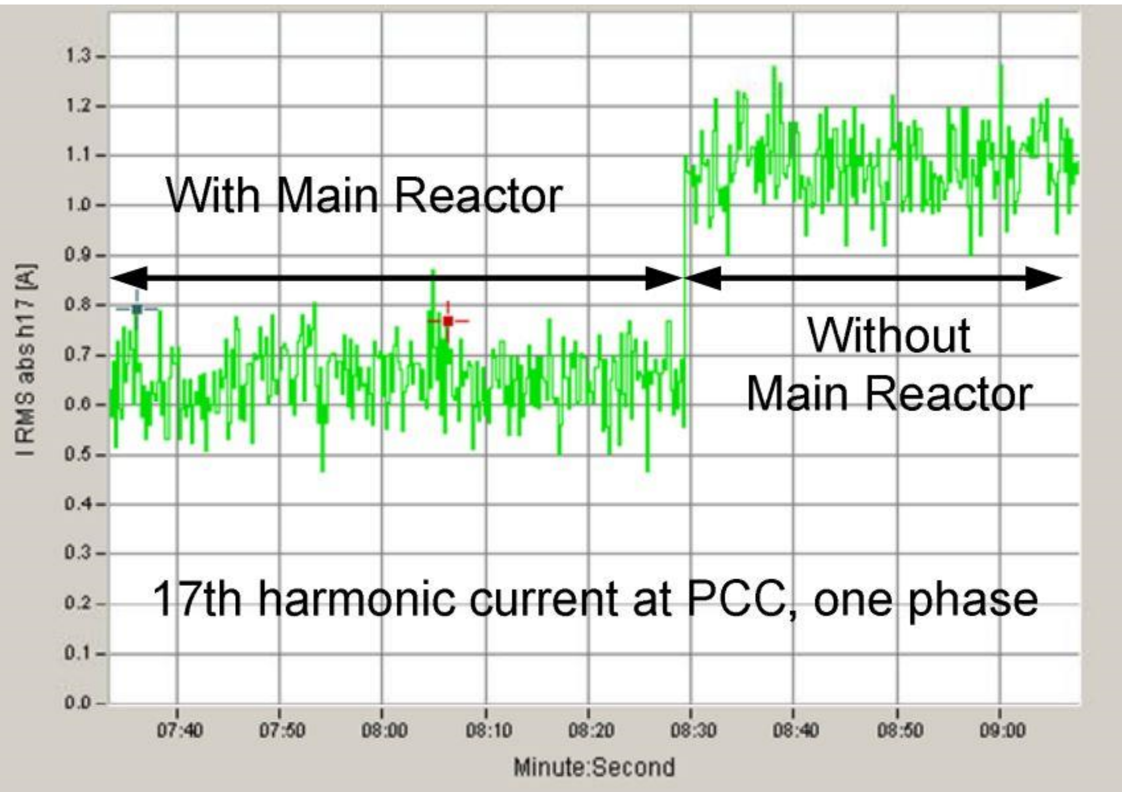

Figure 4.3 *17th harmonic current at PCC, with and without Main Reactor [2]*

Another purpose for a harmonic filter on the auxiliary busbar is to manipulate the network impedances seen from the SVC busbar. With the appropriate tuning of the filter, resonant frequencies of the network can be set to desired values.

Background distortion causes disturbances to SVC control system and increases component voltage stresses. Filtering improves the overall performance of the SVC and allows smaller component rating [2].

Improved harmonic performance of the Main Reactor SVC enables operation even in harsh network conditions. Better tolerance for background distortion and lower harmonic output makes it possible to fill customers’ requirements also in cases where traditional SVC does not come into question.

4.2.2 Operation without TSCs

One specific feature of a Main Reactor SVC is high voltage variation on the SVC busbar in a function of reactive power output of the SVC. This effect is shown in figure 4.4. Figure 4.4 presents the SVC busbar voltage in two practical cases, one with a Main Reactor SVC and the other with a conventional SVC.

The reactive power of the harmonic filters depends on the busbar voltage. Due to the decrease in the SVC busbar voltage, capacitive power of the filters is very low during the inductive operation of the Main Reactor SVC. Capacitive power of the filters is approximately 3-5 times higher in capacitive operation region, than in inductive operation region. In other words, in the case of Main Reactor SVC, harmonic filters act more like TSCs than fixed capacitors.

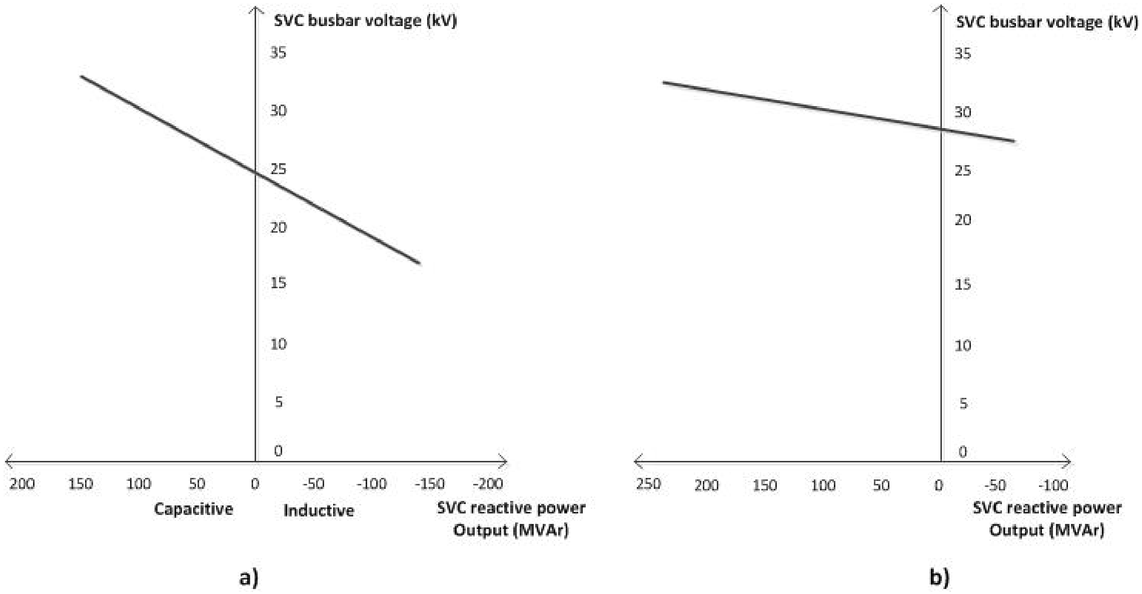

Figure 4.4 *SVC busbar voltage as a function of SVC reactive power output in two installations a) with a Main Reactor SVC and b) with a conventional SVC. Note that the PCC voltage is constant 1.0 pu throughout the range in both cases.*

The SVC configuration without TSCs has several benefits compared to the conventional SVC design. The main benefits are smaller footprint and better step response. According to case studies, footprint of the SVC can be reduced up to 40% with a Main Reactor design. Furthermore, reduced number of the components leads to higher reliability and lower costs.

TSC switching always produces transients to the grid voltage. Especially in weak networks, TSC switching can lead to harmful overvoltage. Eliminating the need for TSC with the Main Reactor configuration, control range of the SVC stays continuous and transients on the grid voltage can be avoided.

4.3 Optimized design with the Main Reactor

Normally, more than one possible solution for the preliminary SVC configuration can be found. The main idea behind the designing process is to find the most cost-effective solution that fulfils all customer requirements.

In a SVC project, there are several factors influencing the final price of the system including the power rating, required performance, restrictions related to configuration, layout and noise emissions and requirements related to losses and reliability of the SVC.

Sometimes parts of the configuration, for example the number of some components or branches, could be fixed by the customer. This may rule out some system configurations from the design, including the most cost-efficient one.

4.3.1 Requirements for the harmonic performance

Harmonic performance requirements defined by the customer usually have a high impact on the optimal SVC configuration. Commonly applied harmonic performance indicators for SVC are listed below. Minimum requirements, definitions and calculation principles can be found from standards [11, 12].

- Total harmonic distortion (THD) for voltage.
- Individual harmonic distortion for voltage and current.
- Telephone influence factor (TIF).
- I-T product.

Total harmonic voltage distortion, individual voltage distortion and TIF relate to the voltage distortion at PCC. I-T product and current distortion relate to the harmonic current injected from SVC to the grid.

Strict requirements for the SVC performance with severe harmonic characteristics and impedances of the network can reduce the number of possible configurations considerably. The superior harmonic performance of Main Reactor SVC increases the possibility to optimize the SVC configuration during the designing process.

4.3.2 Layout

The land area reserved for the SVC installation is typically limited by the customer. A strictly limited area may be problematic if several branches are required due to the large power range or demanding harmonic conditions. The Main Reactor SVC is an optimal solution in cases where high harmonic performance and minimized footprint are required at the same time.

It should be noted that, the cost of the civil works depends on the size of the layout. By reducing the footprint of the installation, costs related to the civil works can be reduced with the Main Reactor SVC.

5. FEASIBILITY OF DIFFERENT TECHNOLOGIES

Designing the optimal compensation system is a complicated and long procedure. The process is always affected by many technical, commercial and environmental aspects. Each project has a set of requirements, and a case specific solution is always the best to meet those requirements.

This chapter compares the feasibility of the traditional SVC, Main reactor SVC and STATCOM solutions from different points of view. The objective for this chapter is to find out the most important factors affecting the designing process and to set out guidelines for selecting the most cost-effective solution for different situations.

5.1 Technical specification

At the beginning of a SVC/STATCOM inquiry, a potential customer issues a request for tender, which is available to all potential suppliers. Request for tender includes technical specification, which describes the main technical characteristics of the compensation system. Topology of the compensator and parts of the configuration can already be specified or the tenderer may have to choose the best solution from different alternatives.

Requirements of the technical specification may have a strong influence on the applicable technology and possible system configurations. Strict requirements can also rule out some configurations, usually related to SVC based solutions. Restrictions related to the configuration will always reduce the possibility to find the most cost-effective solution. However, if the desired technology is not clearly defined by the customer, the freedom to compare different solutions will be left for the tenderer.

5.2 Commercial aspects

If more than one tender fulfils the set requirements, the decision is normally influenced by the overall price of the purchase. The overall price includes the price of the equipment, installation and lifecycle costs of the compensator.

Lifecycle costs include costs related to maintenance and real power losses of the compensator. These costs must be evaluated for the whole life cycle of the compensator, which is typically around 40 years. Loss valuation has a significant impact on the viability of different configurations.

It should be noted that, the compensation system is usually acquired to achieve savings in the power system operation. Savings related to the optimization of the transmission capacity, prevention of large disturbances or real power losses in the transmission lines can be significant compared to the costs of the compensation system.

5.3 Harmonic performance

Requirements for the harmonic performance vary greatly among different projects. Typically, the compensator is allowed to inject some distortion into the network [12], but sometimes the level of existing distortion must be even reduced with the compensator.

As the IEEE 519 standard [11] defines, the allowed voltage distortion at PCC depends on the PCC voltage. Table 5.1 presents the maximum limits for voltage distortion with different voltage levels.

Table 5.1 *Voltage distortion limits at PCC [11]*

Bus voltage at PCC	Individual harmonic (%)	THD (%)
V ≤ 1.0 kV	5.0	8.0
1.0 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

As mentioned in chapter 3.3.2, STATCOM has an advantage in harmonic performance compared to SVC based system. However, sufficient harmonic performance can usually be achieved also with SVC based solutions, especially with the Main Reactor SVC.

5.3.1 Network impedances

Due to the risk of resonance between the compensator and the network, the network impedance is one of the most important factors during the design process [5]. Every power system has its own impedance description and value of the impedance determines the level of voltage distortion caused by the injected harmonic current at a certain frequency.

Network impedances change over time due to the changes in operation conditions of the network. Therefore it is important that the representation of the impedance values covers all possible values [5].

Possible impedance values for harmonic frequencies under different operation conditions are typically modeled as numerical values or envelope diagrams [5]. Normally, shape of the envelope is a circle, a sector or a polygon. Figure 5.1 illustrates a general impedance sector diagram.

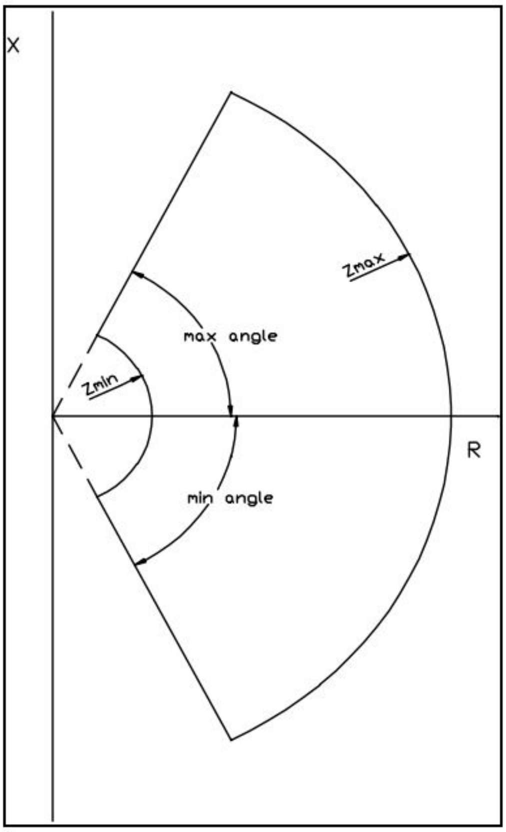

Figure 5.1 *A general sector for power system impedance [5]*

5.3.2 Effects on the designing processes

Especially, harmonic performance requirements and network impedances impact the SVC design process. Higher number of harmonic filters required increases costs related to components, civil works and losses of the compensator. Sometimes TCR must be divided into smaller units to reduce the generation of harmonic distortion.

Challenging impedances with strict limits for harmonics can rule out the use of conventional SVC. In that case, possible alternatives are Main Reactor SVC and STATCOM.

Main configuration of STATCOM can be kept unchangeable despite changing requirements. In some cases, shunt-connected harmonic filter is needed to reduce the harmonic distortion generated by the VSC. However, the size of the filter is notably smaller than the filters used in SVC.

5.4 Dynamic performance

Extensive dynamic analysis always requires detailed modeling and simulations. With careful designing, both SVC and STATCOM can provide a sufficient result to meet the requirements in utility solutions.

Main Reactor SVC without a TSC can provide better dynamic performance compared to the conventional SVC. The dynamic performance of a STATCOM including mechanically or thyristor switched elements does not differ from SVC.

In practical cases, response time of STATCOM is typically 1.5 - 2 voltage cycles. Hence it is slightly faster than SVC that has a response time of typically 2 - 3 cycles. However, faster response time of the STATCOM does not give remarkable benefits with respect to voltage control, transient stability or power oscillation damping in utility solutions [16].

Network effect of the SVC mainly depends on the size of TSCs and TCRs. Switching of a large TSC or thyristor switched reactor (TSR) can cause overshooting or oscillation in weak networks. To minimize undesirable network effects, the MVA rating of switched elements should be in correct proportion to the short-circuit level of the network. The same applies to a STATCOM with switched elements.

5.5 Rating

The customer typically defines rating of the compensation system in technical specification. A ratio between the rated power of the compensation device and short-circuit level of the network is typically from 5 to 10 %.

Requirement for maximum capacitive power of the compensation system is often higher than for inductive power. Rating of the SVC can be defined to cover the required operation range exactly. Symmetrical operation range of the STATCOM can be extended by additional shunt capacitor or reactor branches.

Additional reactive power sources are often needed with unsymmetrical operation range to avoid oversizing of the STATCOM converter. These hybrid STATCOMs incorporate mechanically or thyristor switched branches to provide a switchable offset for STATCOM output. Thyristor controlled reactors are not needed since the output of the converter is controllable.

Price of the SVC, or STATCOM, depends on the rated power and oversizing always decreases the cost-efficiency. The transformer is the most expensive single component in both systems and its price is dependent on the rating. Rating of the transformer should be equal to maximum rated power of the SVC or STATCOM.

5.5.1 STATCOM rating

Rating of the STATCOM is generally limited by the maximum allowable junction temperature of the semiconductor switches [17]. This determines the current rating of one inverter bridge. Voltage capacity of the STATCOM can be increased by adding more series connected IGBT-discs to a single valve. Higher current capacity can be achieved by installing parallel IGBT-valves.

The output current of the STATCOM is not dependent on the power system voltage, as long as the DC capacitor voltage is sufficient. However, DC-capacitors and the IGBT-valves of the STATCOM are sensitive to overvoltage. Therefore SVC endures overvoltage better than STATCOM.

5.5.2 SVC component rating

Component rating calculations are generally based on the worst-case operation conditions. Higher component rating always means higher costs. Main Reactor implementation reduces current and voltage stresses in many SVC components compared to the conventional SVC.

In Main Reactor SVC, high voltage fluctuation on the SVC busbar reduces both current and voltage stresses in TCR valve. Thyristor voltage in TCR valve depends on the product of the SVC bus voltage and the sine of the thyristor firing angle. Value of the sine function is the smallest when bus voltage is the highest. This happens during maximum capacitive output when the firing angle is close to 180 degrees. Compared to the conventional SVC, TCR current of the Main Reactor SVC can be lower during inductive operation due to the reduced capacitive power of the harmonic filters.

Main Reactor also reduces the short-circuit current on the SVC busbar. Therefore the rating of busbars, disconnectors and other equipment can be reduced.

5.6 Reliability and availability

SVC can be considered as a proven technology, with reliability that can be assessed accurately through practical experiments. Annual availability for the SVC can be up to 99.7 % [6]. Compared to the conventional SVC, the reduced amount of components in the Main Reactor SVC leads to an even higher reliability.

As a new technology, reliability of the STATCOM has not reached the same level as the SVC yet. If the customer requires very high reliability, SVC might be more secure alternative compared to STATCOM.

5.7 Footprint

Area reserved for the compensator is normally limited. Strict limitations may prefer STATCOM based solutions, which eliminate the need for bulky reactors and capacitor banks. However, STATCOM requires a large building for IGBT-valves, and a Main Reactor based solution can provide a more compact SVC configuration.

Footprint of the SVC can be reduced, for example, by layering components. This kind of special installation increases costs and their influence on the rating of components must always be evaluated with care.

5.8 Environmental factors

The importance of environmental factors is naturally greater around residential areas. Requirements may be set for different objects, including noise emissions and landscaping [12].

Noise intensity outside the substation may be limited to a certain level [12]. Therefore noise emissions of the compensation device must be taken into account during the design process. Generally, STATCOM produces less noise than SVC due to the absence of large shunt reactors [17].

In SVC based solutions, the source for noise is typically a large TCR. TCR noise level depends on firing angle of the TCR thyristor valve, which affects the form of the harmonic current spectrum and the reactive power of the reactor. Noise of the TCR can be reduced by careful designing and dimensioning of the reactor or by splitting a large TCR into two smaller units.

Sometimes enclosures or noise barriers are needed to reduce the noise impact. The need for strong noise abatement may have significant influence on the costs of the installation and civil works.

Bulky components or high noise barriers may be problematic from the perspective of landscaping. In a situation where these issues prove to be problematic, a technically and economically suitable solution should be negotiated with the customer.

6. CASE STUDY

Designing the main circuit configuration of SVC or STATCOM has a major role in the tendering process. This chapter introduces a case study that compares the conventional SVC, Main Reactor SVC and STATCOM based solutions.

All the solutions presented in this chapter are designed to fulfil the requirements in all the operating conditions. The purpose of this study is to figure out how the different technical solutions, based on conventional SVC, Main Reactor SVC and STATCOM, would affect the implementation and the final price of the project.

Network data presented in this chapter was generated in order to simulate realistic project criteria. Different configurations were compared to gather the best possible solution. However, due to the large amount of variations, there may not be just one definite solution.

6.1 Technical specification

The most important requirements for the technical specifications of the compensation system are given in this chapter. The information is based on the request for tender delivered by the customer of this fictitious project.

The requirements for rating, performance, layout, reliability and availability, audible noise and loss evaluation of the compensator are presented. In addition, the most important data related to the power system characteristics is presented.

6.1.1 Power system characteristics at PCC

Main parameters related to the power system characteristics are presented in table 6.1. The compensator must be rated to withstand these voltage and frequency variations listed overleaf.

Table 6.1 *Power system characteristics at PCC*

Description		Value
System voltage (kV)	Nominal	230
Connection voltage range (kV)	Normal	225…250
	Minimum (continuous)	220
	Maximum (continuous)	260
	Maximum (2 s)	276
	Minimum (500 ms)	161
Short circuit level, 3-phase RMS (MVA)	Maximum	15935
	Minimum	1593
Frequency variations (Hz)	Nominal	60
	Normal	60 ± 0.06
	Maximum (continuous)	60 ± 0.2
	Maximum (short-term)	60 ± 1.5
Voltage unbalance between phases (%)	Up to 1 minute	1
	Sustained	1

6.1.2 Rating

Requirements for the compensator rating are listed below.

- Nominal output of the compensator shall be 300 MVAr capacitive power and 100 MVAr inductive power, both at 1.0 pu voltage at PCC and nominal system frequency (60 Hz).
- Voltage reference for the compensator voltage control shall be adjustable between 0.98 pu and 1.09 pu.
- Slope of the V/I characteristics shall be adjustable between 0 % and 10 % in steps not greater than 0.5 %.
- Reactive power shall be absorbed in a controllable manner down to voltage 0.6 pu at PCC.
- Reactive power shall be generated in a controllable manner up to voltage 1.2 pu at PCC.

6.1.3 Dynamic performance

Step response of the compensation system must meet the following criteria. The change of the measured system voltage must reach 90 % of the steady state value within 50 ms of the initiating control signal of voltage reference. The voltage reference step must be sized to cause system output to change from 60 % of its inductive limit to 60 % of its capacitive limit.

The maximum overshoot must not exceed 10 % of the steady state value. The settling time, which after the voltage must be within ± 5 % of the steady state value, must not exceed 100 ms. Figure 6.1 visualizes the requirements for the step response.

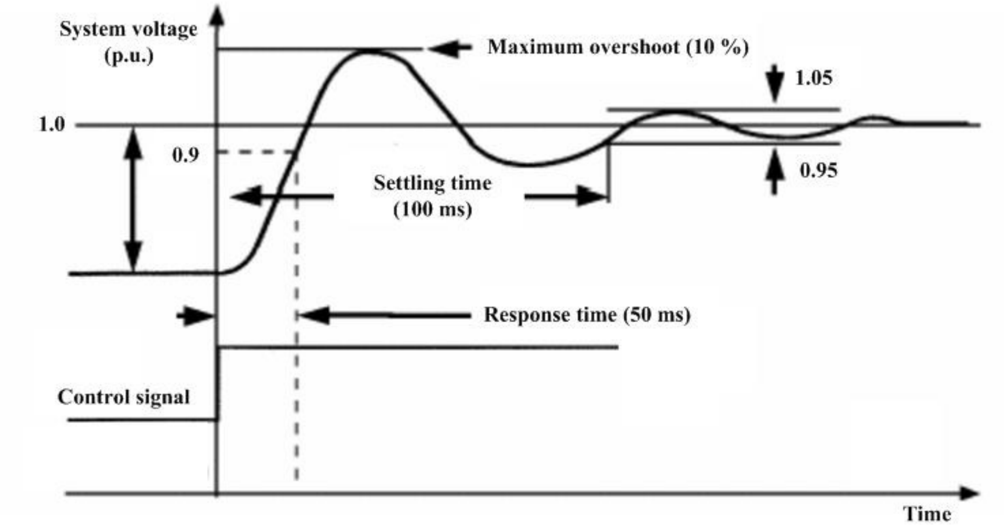

Figure 6.1 *Step response criteria [12]*

6.1.4 Harmonic performance

The maximum voltage distortions at PCC are based on IEEE Standard 519-2014 [11]. Distortion limits are defined by the distortion produced by the compensation device.

Limits for the individual voltage distortion and THD are 1.0 % and 1.5 %, respectively. I-T product at PCC shall be less than 10 000 and TIF shall be less than 50.

6.1.5 Network impedance

Impedance sectors of the network for harmonic frequencies up to 50th (3000 Hz) are presented in Appendix A. Diagrams for the 3rd, 5th and 7th harmonic impedance sector can be found from Appendix B.

Harmonic impedance sectors from 2nd to 7th are defined by the customer. Due to the insufficient customer data, sectors from 8th to 50th are estimations of probable impedance values in weak networks.

6.1.6 Loss evaluation

Total losses should be evaluated at 8500 €/kW with a percent weighting for different operation ranges listed below. Average values for these operation ranges should be calculated with 10 MVAr steps.

- 15 % at capacitive output from 300 to 70 MVAr.
- 80 % at output range from 70 MVAr capacitive to -40 MVAr inductive.
- 5 % at inductive output from -40 MVAr to -100 MVAr.

6.1.7 Reliability and availability

The annual availability for forced outages for the compensator must be at least 99 %. Four (4) forced outages are allowed per year at most. The annual availability in percent is defined by duration in hours as given by [12]

$$\left[1 - \sum \frac{Duration\ of\ equivalent\ outage}{8760}\right] \cdot 100. \tag{6.1}$$

The annual availability must be guaranteed for five years.

6.1.8 Audible noise

The level of audible noise shall be minimized without significant price increase. Audible noise of equipment shall meet the limits specified in relevant IEEE/ANSI standards [12] under normal and the worst operating conditions.

Noise level inside the protection and control room shall not exceed 50 dB and 80 dB in other rooms, where personnel are permitted during operation. The outdoor audible noise level must be specified and guaranteed by measured 3 meters away from each noise critical component.

6.2 Configurations

According to the network data and requirements presented, optimized configurations for both SVCs and a STATCOM are presented in this chapter. Every configuration is optimized to find out the most economical solution that meets all requirements determined by the customer. Configurations are designed with non-commercial simulation programs. Manufacturing tolerances used in the simulations can be found from table 6.2.

Table 6.2 *Component manufacturing tolerances*

Component parameter	Tolerance (%)
TCR reactor inductance	-3…0
Filter reactor inductance	-3…0
Main reactor inductance	-2…2
VSC coupling reactor inductance	-2…2
Capacitor capacitance	-0.75…0.75
Transformer short-circuit impedance	-5…5
Transformer open winding turns ratio	-0.2…0.2

6.2.1 Conventional SVC

Main configuration of the conventional SVC designed for this study is presented in figure 6.2. This SVC consists of three TCRs, two TSCs and three harmonic filters tuned to 5th, 7th and 12th harmonic frequencies.

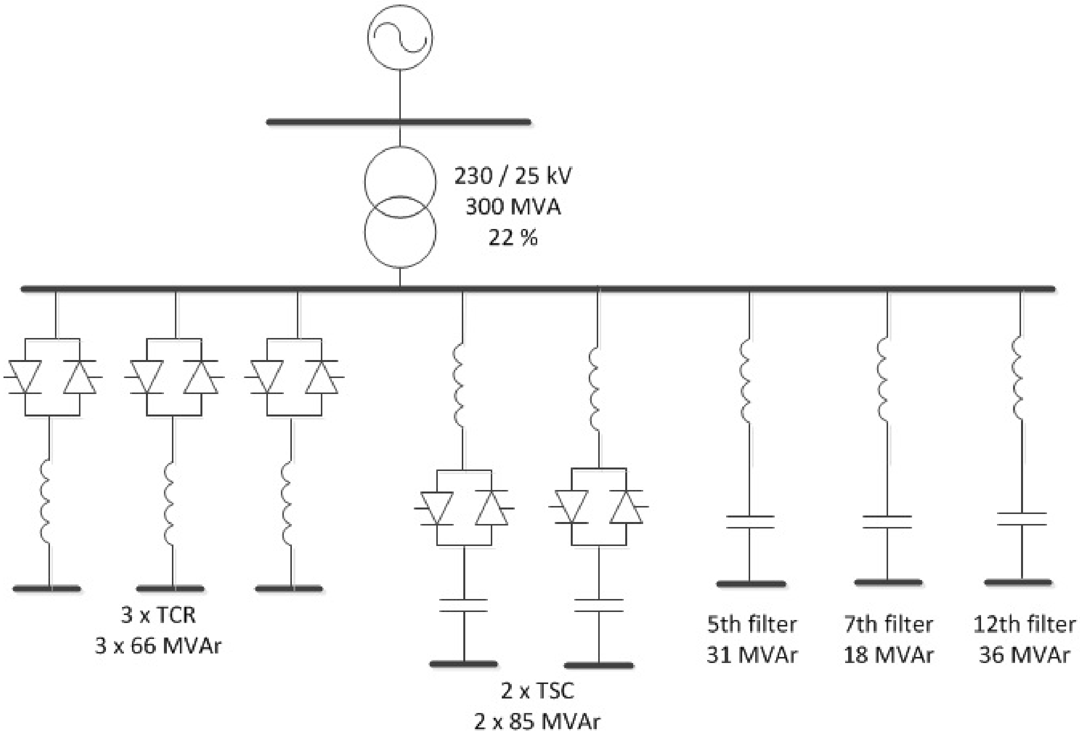

***Figure 6.2** Configuration of the conventional SVC*

Due to the challenging network impedances, several TCRs and harmonic filters are needed to fulfill the harmonic requirements. Harmonic requirements could be achieved with two TCRs and higher filter power as well. However, higher filter power would lead to too high losses. Three TCRs are a compromise between costs related to components and losses. Table 6.3 presents main characteristics and component parameters of this configuration.

Table 6.3 *Main equipment parameters, conventional SVC*

Main equipment parameters	**Value**
Short-circuit current at:	
SVC bus	30 kA
Maximum continuous overvoltage for:	
SVC bus	33 kV
TCR (all):	
Design power	66 MVAr
I_{max} continuous	940 A
TCR harmonic currents:	
3rd	130 A
5th	47 A
7th	24 A
TSC (both):	
Design power	85 MVAr
I_{nom} at 60 Hz	1100 A
5th harmonic filter:	
Design power	30 MVAr
Tuning frequency	299 Hz
I_{nom} at 60 Hz	710 A
7th harmonic filter:	
Design power	18 MVAr
Tuning frequency	418 Hz
I_{nom} at 60 Hz	420 A
12th harmonic filter:	
Design power	36 MVAr
Tuning frequency	718 Hz
I_{nom} at 60 Hz	820 A

6.2.2 Main Reactor SVC

Configuration of the Main Reactor SVC of this study is illustrated in figure 6.3. This SVC solution includes a Main Reactor, a TCR, a TSC and two harmonic filters tuned to 5th and 7th harmonic frequencies.

It should be noted that, harmonic requirements could be achieved with considerably simpler configuration than without the Main Reactor. One large TCR can be used due to improved harmonic performance compared to the conventional design.

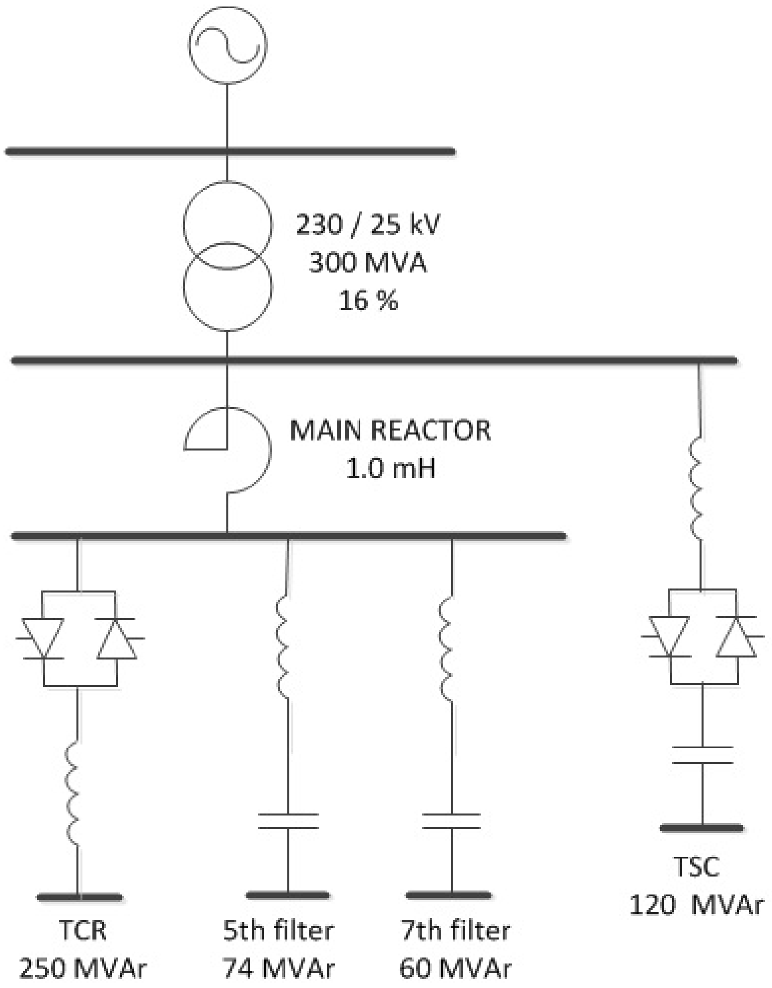

Figure 6.3 *Configuration of the Main Reactor SVC*

Table 6.4 presents main characteristics of this configuration. Compared to the conventional design, short-circuit current at SVC-bus has reduced from 30 kA to 22 kA. This allows a reduced rating for the SVC-busbar and the disconnectors in the SVC-bus. However, short-circuit current at Aux-bus is higher than in the SVC-bus, 41 kA.

Table 6.4 *Main equipment parameters, Main Reactor SVC*

Main equipment parameters	**Value**
Short-circuit current at:	
SVC bus	20 kA
Aux bus	41 kA
Maximum continuous overvoltage for:	
SVC bus	33 kV
Aux bus	32 kV
Main Reactor:	
Inductance	1.0 mH
I_{max} continuous	2.6 kA
TCR:	
Design power	250 MVAr
I_{max} continuous	3.0 kA
TCR harmonic currents:	
3rd	420 A
5th	150 A
7th	80 A
TSC:	
Design power	120 MVAr
I_{nom} at 60 Hz	1.6 kA
5th harmonic filter:	
Design power	74 MVAr
Tuning frequency	298 Hz
I_{nom} at 60 Hz	1.7 kA
7th harmonic filter:	
Design power	60 MVAr
Tuning frequency	418 Hz
I_{nom} at 60 Hz	1.4 kA

6.2.3 STATCOM

The STATCOM based solution consists of two VSCs, two TSCs and a STATCOM filter. Due to the unsymmetrical operation range, the TSCs are included to avoid oversizing of the VCSs. The configuration is illustrated in figure 6.4.

It should be noted that, the harmonic filter required with the STATCOM is considerably smaller than filters in the SVC solutions. TSC is a cost-effective solution to provide capacitive power and to extend the operation range of the STATCOM, while maintaining the fast response time of the compensator.

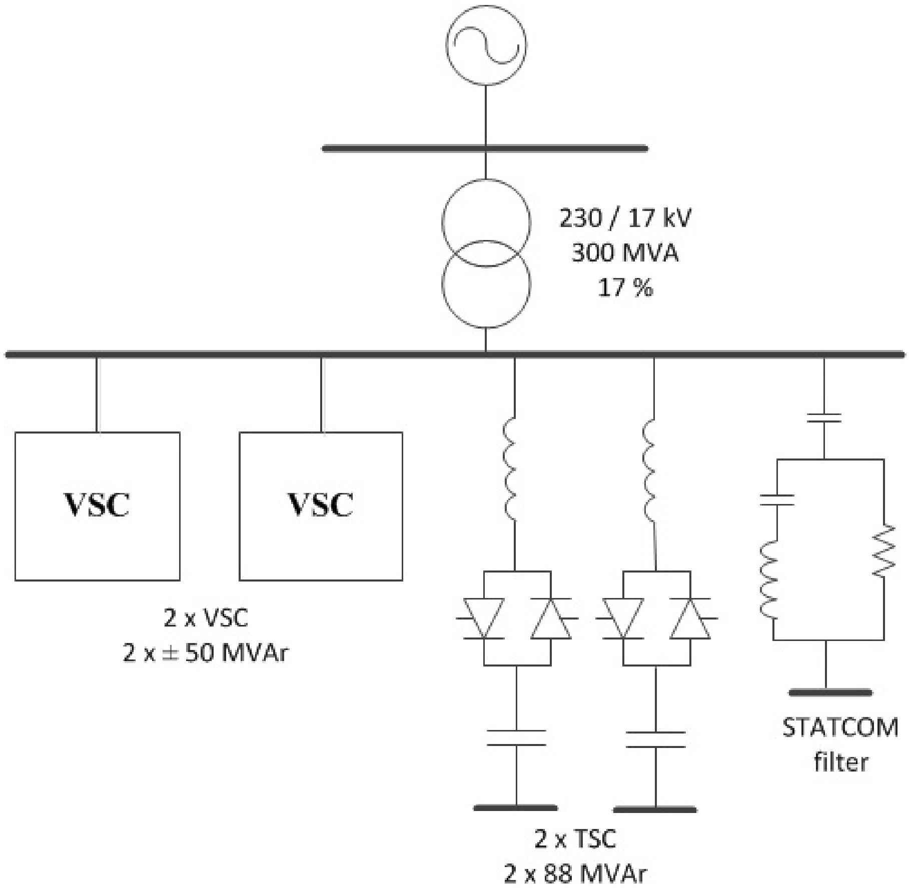

Figure 6.4 *Configuration of the STATCOM*

Both VSCs utilize MMC technology with several series-connected submodules. STATCOM filter is included to provide an even smoother VSC output voltage. Table 6.5 presents main characteristics and component parameters of this configuration.

Table 6.5 *Main equipment parameters, STATCOM*

Main equipment parameters	Value
Short-circuit current at: STATCOM bus	 59 kA
Maximum continuous overvoltage for: STATCOM bus	 21 kV
VSC (both): Design power Rated current	 ± 50 MVAr 1.0 kA
TSC (both): Design power I_{nom} at 60 Hz	 88 MVAr 1.7 kA

6.3 Performance

All the solutions were designed to fulfill requirements related to harmonic and dynamic performances in every operation point. Detailed inspection of the dynamic performance results has not been made in this study as the performance exceeding requirements have not been evaluated by the customer. However, dynamic performance of the STATCOM can be assumed to be marginally better compared to SVC based solutions.

Tables 6.6, 6.7 and 6.8 present harmonic performance of the conventional SVC, the Main Reactor SVC and the STATCOM, respectively. Tables include worst-case values for TIF, I-T product, THD and individual voltage distortion at PCC.

Table 6.6 *Harmonic performance at PCC, conventional SVC*

Parameter	**Limit**	**Worst case value**
TIF	50	38
I-T	10 000	8400
THD (%)	1.5	1.3
Individual harmonic voltage distortion (%)	1.0	< 1.0

Table 6.7 *Harmonic performance at PCC, Main Reactor SVC*

Parameter	**Limit**	**Worst case value**
TIF	50	47
I-T	10 000	9200
THD (%)	1.5	1.2
Individual harmonic voltage distortion (%)	1.0	< 1.0

Table 6.8 *Harmonic performance at PCC, STATCOM*

Parameter	**Limit**	**Worst case value**
TIF	50	42
I-T	10 000	5400
THD (%)	1.5	0.33
Individual harmonic voltage distortion (%)	1.0	< 1.0

Analyses of the configurations and harmonic performances of both SVCs prove that implementation of the Main Reactor enables considerably better harmonic performance compared to the conventional SVC design. However, harmonic performance of the STATCOM is slightly better compared to both SVC based solutions.

6.4 Loss evaluation

Loss prices for different operation points have been presented earlier in chapter 6.1.6. Loss curves for all compensators are represented in figures 6.5, 6.6 and 6.7.

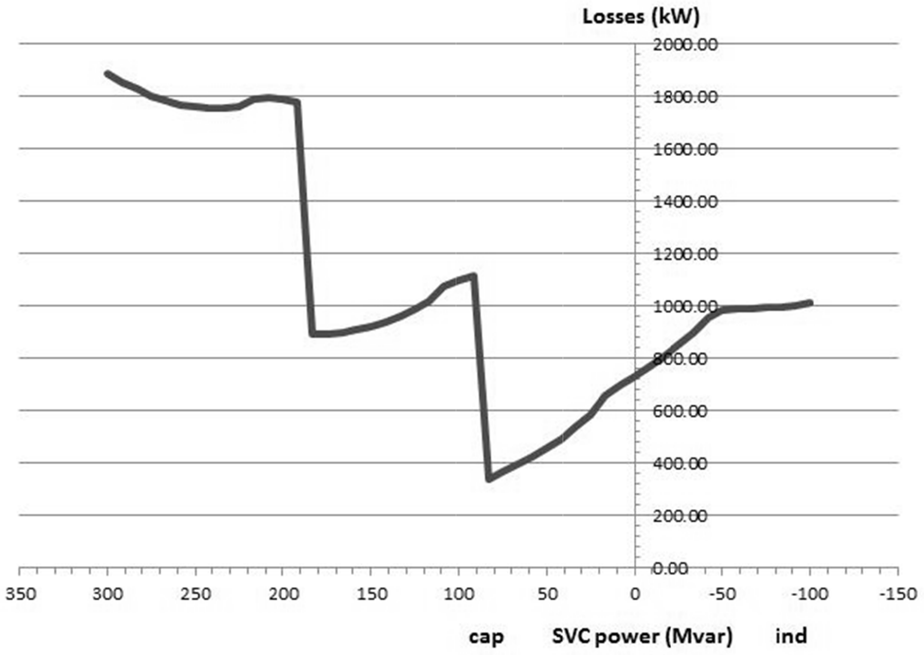

Figure 6.5 *Loss curve for the conventional SVC*

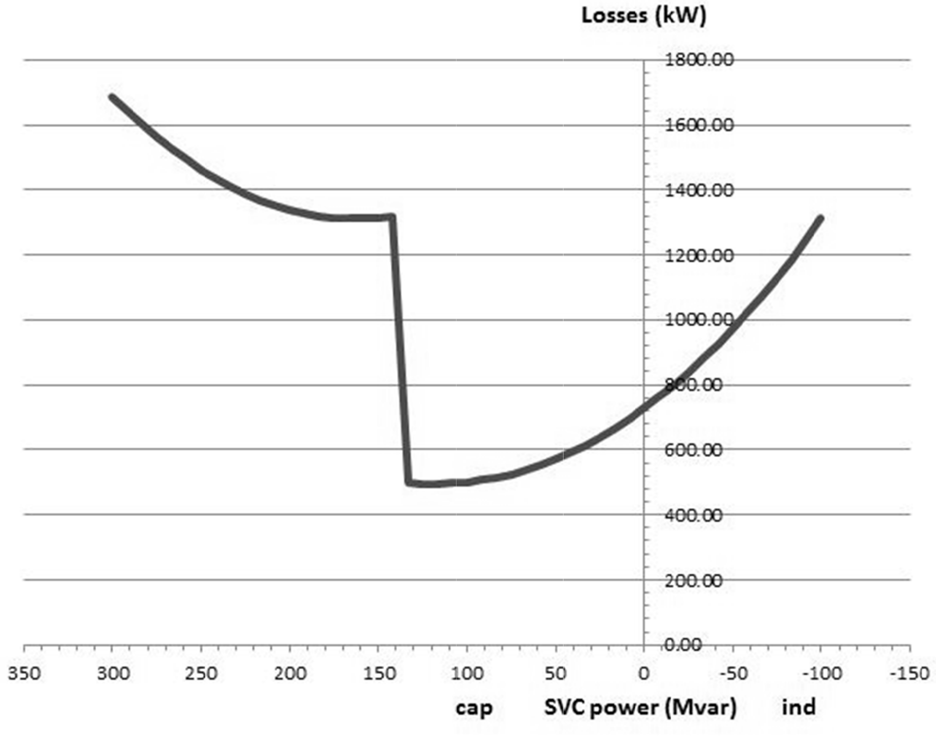

Figure 6.6 *Loss curve for the Main Reactor SVC*

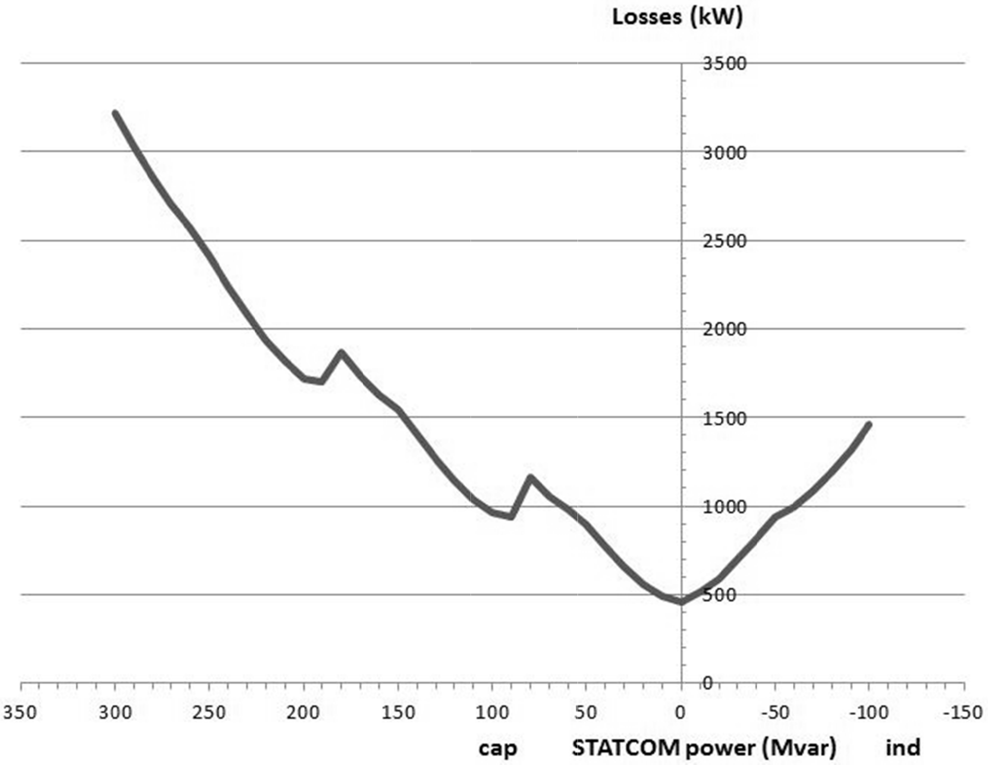

Figure 6.7 *Loss curve for the STATCOM*

Total loss price for the conventional SVC can be calculated as follows:

- Average losses from 70 MVAr (cap) to 300 MVAr (cap): 1330 kW,
- from 70 MVAr (cap) to -40 MVAr (ind): 669 kW,
- from -40 MVAr (ind) to -100 MVAr (ind): 994 kW.
- Total cost: 8500 €/kW·(0.15·1330 kW+0.80·669 kW+0.05·994 kW) = 6 667 400 €.

By using the same calculation procedure, total loss price for the Main Reactor SVC is:

- Average losses from 70 MVAr (cap) to 300 MVAr (cap): 1420 kW,
- from 70 MVAr (cap) to -40 MVAr (ind): 703 kW,
- from -40 MVAr (ind) to -100 MVAr (ind): 1130 kW.
- Total cost: 8500 €/kW·(0.15·1420 kW+0.80·703 kW+0.05·1130 kW) = 7 071 150 €.

Further, total loss price for the STATCOM is:

- Average losses from 70 MVAr (cap) to 300 MVAr (cap): 1830 kW,
- from 70 MVAr (cap) to -40 MVAr (ind): 674 kW,
- from -40 MVAr (ind) to -100 MVAr (ind): 1160 kW.
- Total cost: 8500 €/kW·(0.15·1830 kW+0.80·674 kW+0.05·1160 kW) = 7 409 450 €.

Compared to the conventional SVC, evaluated average losses of the Main Reactor SVC are higher during the whole operation range due to higher filter power and the Main Reactor itself. However, weighting on the operation ranges impacts the results.

Losses of the STATCOM are the lowest during low output and increase substantially with the output power. Evaluated overall losses of the STATCOM are slightly higher compared to SVC based solutions.

6.5 Footprint

Size of the land area required for the compensation device is quite easy to estimate broadly, when the main configuration has been defined. In this study, estimates for the footprints of all devices were defined without extensive layout design. Results can provide good initial data for the relative difference in costs related to the civil works.

Land area required for the STATCOM configuration of this study can be estimated to be 60 - 70 % of the area required for the conventional SVC configuration. For the Main Reactor based solution, required land area can be estimated to be 70 - 80 % of the conventional design.

6.6 Cost evaluation

A rough cost analysis of each system was carried out, to compare the expenses of different systems. However, a detailed cost analysis and division of costs are not included in this thesis.

Cost evaluation includes costs related to investment cost of the equipment and losses of the systems. Civil work costs are not included in the comparison. These costs vary broadly between different countries and are difficult to quantify for such cost evaluation purposes.

Compared to the conventional SVC, costs of the Main Reactor SVC are approximately 10 - 20 % lower due to simpler configuration. Costs of the STATCOM are approximately 20 - 30 % higher compared to the conventional SVC, due to more expensive technology.

6.7 Selection

In order to facilitate the comparison between different alternatives, a simple comparison tool was developed in Microsoft Excel. This tool takes into account how the customer values different features of the compensator and gives a rating for conventional SVC, Main Reactor SVC and STATCOM based solutions.

The developed comparison tool focuses on following characteristics of compensators: performance, rating, losses, footprint, noise, and RAM. Ratings for different characteristics are based on the data given in the technical specification and weighting factors determined by the system designer to take into account special needs of the customer. Weighting factors have to be reconsidered in every case to ensure the feasibility. Figure 6.8 illustrates the rating of the main characteristics of all designed solutions.

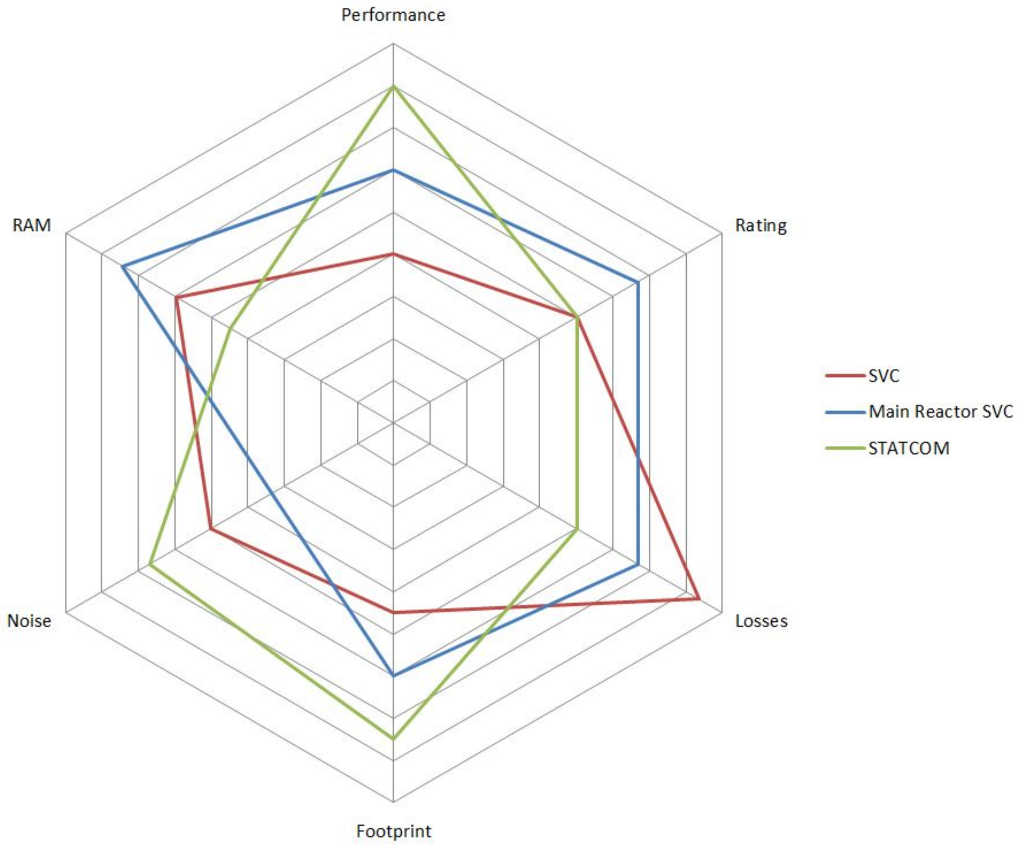

Figure 6.8 *Technical comparison for SVC, Main Reactor SVC and STATCOM*

Taking into account that every solution is designed to fulfill all the requirements, Main Reactor SVC seems to be the most feasible solution for this case. When considering Main Reactor SVC and STATCOM, differences in performance are rather small compared to the differences in costs.

It should be noted that, the background data has a great influence on the outcome. A single minor change in the data may have a significant impact on the results.

7. CONCLUSIONS

This thesis was carried out between November 2015 and April 2016. The purpose of this thesis was to summarize the benefits of the Main Reactor SVC, to find out the most important factors affecting the superiority of the conventional SVC, the Main Reactor SVC and the STATCOM and to discover the most feasible technology to a particular case study.

The study revealed that the most important benefits of the Main Reactor SVC, compared to the conventional SVC, are its improved harmonic performance, reduced footprint and possibility to manipulate the network impedances with harmonic filters. However, the effectiveness of the Main Reactor always depends on the technical requirements for the compensation device and specifications of the power system. The feasibility of the Main Reactor SVC should be discovered in cases where the circumstances are too challenging for the conventional SVC.

The most favorable conditions for the Main Reactor based solutions are complex network impedances, challenging requirements related to harmonic performance and overvoltage operation and unsymmetrical requirements between capacitive and inductive operation ranges.

During the research it was discovered, that generic comparison of Main Reactor SVC, conventional SVC and STATCOM is very challenging. Therefore the comparison between suitable technologies should be done case-by-case.

Results of the case study were congruent with the theoretical assumptions and the Main Reactor SVC proved its technical and economical competitiveness. In this study, investment costs of the Main Reactor based solution were roughly 10 - 20 % lower compared to the conventional SVC. Investment costs of the STATCOM were about 20 - 30 % higher compared to the conventional SVC.

Due to its lower costs, Main Reactor SVC was selected as the most feasible solution for this case study. All the compared solutions fulfilled the requirements, which is why the better performance of the STATCOM did not compensate its higher investment costs.

As this thesis was based on simulated data, some data, especially the civil works costs were more difficult to evaluate. Due to this, the commercial comparison could not be taken further in this thesis, and could be continued in further studies based on this topic. Especially, as it is a significant factor in the decision-making process.

The contents of this thesis successfully met its requirements and it could be expanded in the future to include a comprehensive analysis of dynamic performance and further development of the comparison tool. In order to make the tool useful under varying circumstances, the amount of input data must be increased. In addition, the user interface of the tool would need to be developed to be user-friendlier.

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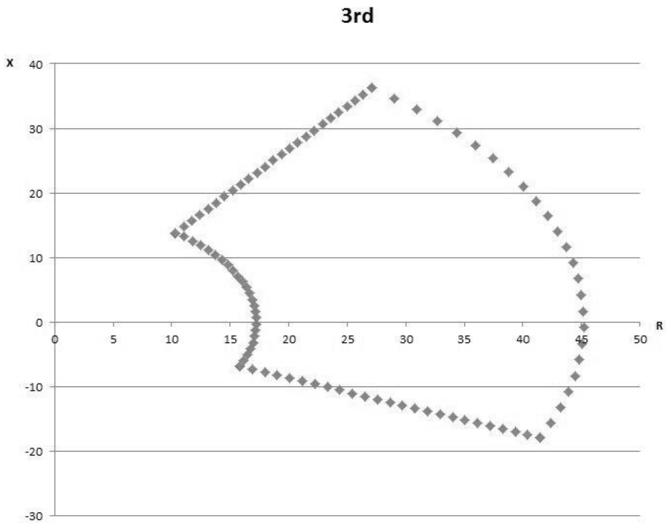
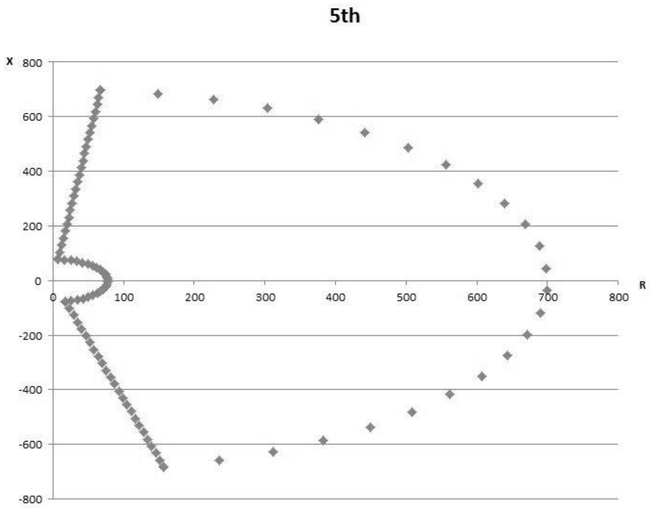
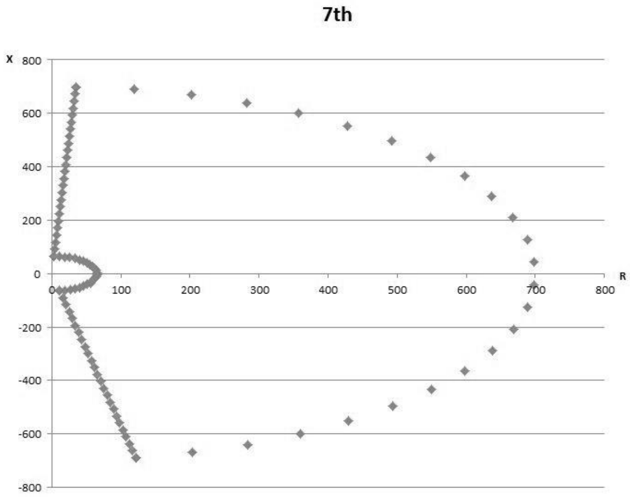
APPENDIX A: NETWORK IMPEDANCES

	Z min (Ω)	**Z** max (Ω)	**α**-min **deg.**	**α**-max **deg.**
2th	15.2	32.2	14.85	77.04
3rd	17.2	45.2	-23.4	53.23
4th	15.8	220.1	-35.19	84.31
5th	78.1	700.0	-77	84.46
6th	38.5	110.3	-28.23	86.98
7th	65.4	700.0	-80	87.13
8th	50.0	163.0	-85	85
9th	50.0	163.0	-85	85
10th	50.0	300.0	-85	85
11th	50.0	330.0	-85	85
12th	50.0	360.0	-85	85
13th	50.0	390.0	-85	85
14th	50.0	420.0	-85	85
15th	50.0	450.0	-85	85
16th	50.0	480.0	-85	85
17th	50.0	510.0	-85	85
18th	50.0	540.0	-85	85
19th	50.0	570.0	-85	85
20th	50.0	600.0	-85	85
21th	50.0	630.0	-85	85
22th	50.0	660.0	-85	85
23th	50.0	690.0	-85	85
24th	50.0	720.0	-85	85
25th	50.0	750.0	-85	85
26th	50.0	780.0	-85	85
27th	50.0	810.0	-85	85
28th	50.0	840.0	-85	85
29th	50.0	870.0	-85	85
30th	50.0	900.0	-85	85
31th	50.0	930.0	-85	85
32th	50.0	960.0	-85	85
33th	50.0	990.0	-85	85
34th	50.0	1020.0	-85	85
35th	50.0	1050.0	-85	85
36th	50.0	1080.0	-85	85
37th	50.0	1110.0	-85	85
38th	50.0	1140.0	-85	85
39th	50.0	1170.0	-85	85
40th	50.0	1200.0	-85	85
41th	50.0	1230.0	-85	85
42th	50.0	1260.0	-85	85
43th	50.0	1290.0	-85	85
44th	50.0	1320.0	-85	85
45th	50.0	1350.0	-85	85
46th	50.0	1380.0	-85	85
47th	50.0	1410.0	-85	85
48th	50.0	1440.0	-85	85
49th	50.0	1470.0	-85	85
50th	50.0	1500.0	-85	85

APPENDIX B: IMPEDANCE SECTOR DIAGRAMS


3rd


5th


7th