Series / Parallel Hybrid VSC-LCC for HVdc Transmission Systems

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Abstract

This thesis investigates the feasibility of hybrid converter based arrangements for High Voltage direct current (HVdc) transmission systems. The conventional HVdc transmission systems, which use Line Commutated Converter (LCC) technology, require ac voltage and large amounts of reactive power to operate; Voltage-Sourced Converter (VSC) based HVdc schemes, on the other hand, while maintaining most of the advantages of LCC-based systems, have overcome a number of disadvantages inherent to conventional LCC systems. Their ability to provide voltage support to very weak ac networks through generating reactive power, while delivering real power, makes them an ideal option for providing reliable power to remote locations. These converters suffer disadvantages such as higher costs, sensitivity to dc-side faults, and smaller ratings in comparison to conventional converters.

This research exploits a new approach and introduces a hybrid configuration of VSC and LCC converters. The hybrid converter combines the advantages of these two converter types, while trying to stay far from their disadvantages. The thesis investigates and discusses the benefits of using VSC-LCC hybrid converters for HVdc transmission systems in stations where support of ac voltage is mostly absent (very weak ac system). It concludes that Series Hybrid Converter (SHC) configuration is a promising option for very weak ac system applications comparing to Parallel Hybrid Converter (PHC) option.

Using simplified mathematical models and extensive effort on digital time simulation with PSCAD / EMTDC program, the technical feasibility of implementing SHC has been demonstrated.

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List of Symbols

D_i	individual harmonic of voltage content
D_{rms}	geometric sum of voltage harmonic content
E_{a1}	fundamental component of system ac voltage
E_{a1}^*	reference value for fundamental component of system ac voltage
E_{sys}	(external) system voltage
ϕ	phase angle (phase shift)
f_0	fundamental frequency
γ	extinction angle
γ^*	extinction angle reference
γ_{error}	extinction angle error
$\gamma_{\min}$	minimum extinction angle
I_{cnv}	system-side ac current of converter
i_d	direct axis current
i_d^*	direct axis reference current
I_{dc}	dc current
$I_{dc,VSC}$	VSC dc current
$I_{dc,LCC}$	LCC dc current
$I_{dc,\mathrm{Re}c}$	rectifier dc current

$I^{*}_{dc,\mathrm{Re}\,c}$	rectifier dc reference current
i_q	quadrature axis current
i_q^{*}	quadrature axis reference current
K	controller gain
K_p	proportional controller gain
K_I	integral controller gain
m	modulation index
n	transformer turn ratio
P_{dc}	dc power
P_{LCC}	LCC real power
P_{VSC}	VSC real power
Q_C	reactive power generation
Q_f	filter reactive power generation
Q_{LCC}	LCC reactive power
Q_{VSC}	VSC reactive power
R	resistance
S_{VSC}	VSC apparent power
S_{LCC}	LCC apparent power
T	controller time constant
$V_{ac,Inv}$	inverter ac voltage (system side)

$V^{*}_{ac,Inv}$	inverter ac voltage reference (system side)
V_{cnv}	converter-side ac voltage
V_d	direct axis voltage
V_q	quadrature axis voltage
V_{dc}	dc voltage
$V_{dc,LCC}$	LCC dc voltage
$V^{*}_{dc,LCC}$	LCC dc voltage reference
$V_{dc,VSC}$	VSC dc voltage
$V^{*}_{dc,VSC}$	VSC dc voltage reference
V_{di}	inverter dc voltage
V_{dr}	rectifier dc voltage
V_{LR}	load rejection voltage
X_L	transformer/reactor inductive reactance
Z_1, Z_2	impedances
Z_f	filter impedance
Z_{fault}	fault impedance
Z_{fp}	parallel hybrid option filter impedance
Z_{fs}	series hybrid option filter impedance

List of Abbreviations

AOI	Inverter Alpha Order
AOR	Rectifier Alpha Order
CCC	Capacitor Commutated Converter
CF	Commutation Failure
CFII	Commutation Failure Immunity Index
CSC	Current-Sourced Converter
EMTP	Electro Magnetic Transient Program
ESCR	Effective Short Circuit Ratio
FCC	Forced Commutated Converter
GTO	Gate Turn Off Transistor
HVdc	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
LCC	Line-Commutated Converter
MAP	Maximum Available Power
MI	Modulation Index
PCC	Point of Common Coupling
PHC	Parallel Hybrid Converter
PI	Proportional Integral
PLL	Phase Locked Loop
PORD	Power Order
PS	Phase Shift
PSCAD	Power System Computer Aided Design

p.u.	Per-Unit
PWM	Pulse Width Modulation
rms	Root Mean Square
SCR	Short Circuit Ratio
STATCOM	Static Compensator
SHC	Series Hybrid Converter
SHEM	Selective Harmonic Elimination Method
SPWM	Sinusoidal Pulse Width Modulation
TCSC	Thyristor Controlled Series Capacitor
THD	Total Harmonic Distortion
VDCOL	Voltage Dependent Current Order Limiter
VSC	Voltage-Sourced Converter

Chapter 1: Introduction

1.1 Overview

High Voltage Direct Current (HVdc) technology is a high-power electronics technology used in electric power systems for bulk power transmission. Reduced power losses, reduced line costs, increased system stability, better control of power flow and fast development of the semi-conductor technology have made the HVdc systems more competitive with ac systems [1]. HVdc is an efficient and flexible method to transmit large amounts of electrical power over long distances by overhead transmission lines or underground / submarine cables. It is also used to interconnect separate power systems, where conventional Alternating Current (ac) connections cannot be used. These systems are being widely used today.

The fundamental process that occurs in an HVdc system is the conversion of electrical current from ac to dc (rectifying) at the sending end, and from dc to ac (inverting) at the receiving end. Converters can be classified based on the method used for commutation, which might be of natural (line, or self), or of forced type. Accordingly they are referred to as Line Commutated Converters (LCC) and Forced Commutated Converters (FCC), respectively. They may also be classified based on how they appear from ac system terminals' point of view, which might be a current- or a voltage-sourced, hence the names Current-Sourced Converters (CSC), and Voltage-Sourced Converters (VSC).

So far, the majority of existing HVdc schemes are built with converter stations with conventional LCC converters. These converters have the advantage of being robust and are able to rapidly control the direct current, e.g. at faults on the dc side. In these converters, the ac current always lags behind the line voltage, due to the firing delay on the thyristors. This means that they always need to consume reactive power, which is a disadvantage (Section 2.4).

The short-comings of the LCC converters for supplying weak ac systems have made it attractive to investigate the possibility of using the forced commutated type converter which are based on the gate-turn-off thyristors (GTOs) or Insulated Gate Bipolar Transistors (IGBTs) (Sections 2.3.1.2 and 2.3.1.3). The commutation in this type of converter is performed independently of the line voltage, which makes it possible to control the converters at the two ends of the dc line such that they both consume and generate reactive power independent of the generated active power. This implies that very weak ac systems and even systems with local generation can be supplied with power using forced commutated converters.

However, these converters are more expensive than the line commutated converters and there is a challenge to stack them in series to generate the required voltage. The VSC converter is most effective at the inverter side as it can provide reactive power and support ac terminal voltage. In this research, only the inverter-hybrid configuration, in the form of series and parallel connection of one LCC and one VSC converter, has been studied in detail and the rectifier is of a conventional LCC type. The performance of the proposed hybrid configurations are compared with conventional arrangement of only LCC type converters. The LCC-type converter used for comparison is the First Cigré Benchmark model (used as the Cigré Benchmark in this thesis) system, as is explained in section 2.9.1

1.2 Ac system strength

The strength of an ac network at fundamental frequency is measured in terms of its Short Circuit Ratio (SCR), which is defined as the ratio of the short circuit MVA of the ac system at the ac busbar with the dc blocked, to the rated dc power of that busbar [2]. This ratio is equivalent to the system Thevenin admittance expressed in per unit with the rated dc power as the MVA base and rated ac voltage as the voltage base. Ac systems connected to converters, have an equivalent ac-network that has to be included in the system representation. This ac equivalent is inversely proportional to the SCR. A network with an SCR smaller than 2 is considered to be a very weak system [2]. The term “weak system” used in this report has the meaning of “electrically weak”, i.e. the ac system with equivalent voltage source behind high equivalent impedance [3].

1.3 Basic features of the CSC and VSC converters

Connecting 3-phase balanced ac sinusoidal voltages to a dc system through a set of switching elements and transformer windings can generate a switching-type ac output. The type of external impedance used on the dc-, or ac-side of the switching element makes the converter a current-sourced converter (CSC), or a voltage-sourced converter (VSC), (Figure 1.1(a) and (b), respectively).

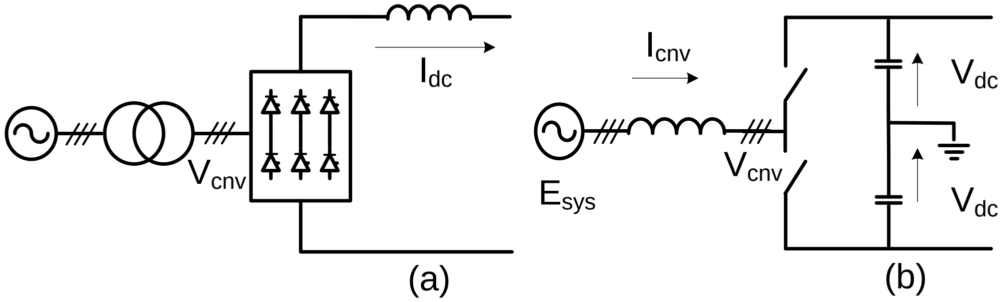

Figure 1.1 Schematics for (a) current-sourced converter, (b) voltage-sourced converter

1.3.1 The current-sourced converter

It can be shown [1] that the dc voltage in current-sourced converters (CSC) is proportional to the ac-side voltage, multiplied by the cosine of the angle between the fundamental frequency component of the alternating phase current and ac-phase voltage. This angle may be controlled by controlling the switching time.

The ac current has a magnitude proportional to the dc current as it is created directly from the dc current by switching, therefore it has harmonics, which need filtering. On the dc side, it acts as a constant current source (I_{dc}) and needs an inductor as its energy storing device; it requires dc filters to operate properly (Figure 1.1(a)). It provides inherent fault current limiting features. The semiconductors used can be of the line, or forced commutated type and switch at line frequency, which brings low switching losses [5]. In CSCs the polarity of the dc voltage would change whenever the angle goes beyond 90 degrees (it changes with dc power flow), but the polarity of dc current cannot change. The valves are commanded to turn on at the appropriate instant by controlling the angle at which the firing pulses are issued. One major advantage of these converters is the possibility of dc voltage control, by controlling the angle at which the firing pulse is issued. The dc fault current can be limited by control action.

1.3.2 The voltage-sourced converter

It can be shown [6] that the dc current in voltage-sourced converter is proportional to the ac-side voltage, multiplied by the sine of the phase displacement angle between the fundamental frequency components of the converter output voltage and the network alternating voltage.

The ac voltage is proportional to the capacitor voltage on the dc side as it is created directly from the dc voltage by switching (Figure 1.1(b)). It also generates harmonics, but the transformer inductance, or an external inductance, helps to filter out the generated harmonics. Some filtering, mostly at higher order components, is usually needed. A VSC does not need reactive power supply. On the dc side it acts as a constant voltage source and needs a capacitor to maintain the voltage constant. It encounters difficulty for dc line side faults because of discharging the capacitor into the fault. It uses self-commutated semiconductors, and switches at high frequencies, which brings higher switching losses [5]. In VSCs the dc current polarity can be altered by reversing the polarity of the mentioned angle (it changes with the dc power flow), but the polarity of the dc voltage cannot change. It may be concluded that the active power flow can be changed by changing the polarity of the dc current. Because of this bi-directionality, the switches must be capable of conducting current in both directions. The dc fault current cannot be limited by control action because of the reverse diodes used in the converter. Here a dc breaker is needed to interrupt the dc fault current.

1.4 Line commutated versus forced commutated converters

The switching circuit, which performs the conversion from dc to ac or ac to dc, can rely on the ac line voltage (which is called Line Commutated Converter, LCC), or not (which is called Forced Commutated Converter, FCC).

1.4.1 Line commutated converters

Line commutated converters rely on the line voltage for performing the commutation of the current. The switching component of LCC converters uses thyristors, which are only capable of conducting current in one direction (Section 2.3.1.1). They start to conduct current when a positive voltage is applied across the valve and a triggering pulse is applied across the gate. The requirement of the positive voltage results in that the ac voltage will always lead the ac current in phase. A consequence of this is that the LCC always absorbs reactive power both in rectifier and inverter, which at rated power amounts to around 60% of their real power rating. During its normal operation, LCC will switch the current periodically from one thyristor valve to the other, in a specified sequence [4]. Failing in a current transfer would cause commutation failure (CF), which probably will cause a (permanent) short circuit between two phases. Figure 1.2. Shows a simple schematic for a line commutated CSC.

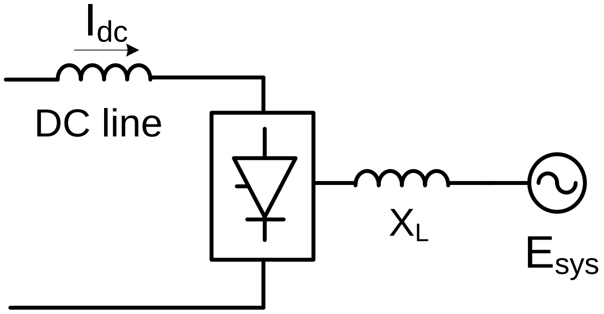

Figure 1.2 Line commutated CSC schematic using thyristor valves

Another type of line commutated converter uses anti-parallel connection of diodes and thyristors as switching elements. In this converter only half of the converters are controllable, which makes dc line fault recovery more difficult. The harmonic content is also higher. Due to these facts such converters are not practically employed [7].

Depending on the voltage / power rating under consideration, the thyristors will be arranged in series, parallel, or series/parallel configurations. Due to their nature, these converters need large external reactive power support [4]; they are sensitive to ac terminal voltage changes and need large amounts of filtering [3]. Thyristor-based LCC converters cannot work under very low SCR conditions without appropriate dynamic voltage control and support of devices such as static or synchronous VAR compensators [8], [9], [10]. The common practice is that even with dynamic voltage support, part of the needed reactive power will be supplied using static VAR generators, in the form of dedicated capacitors / filter capacitors [4].

1.4.2 The forced commutated converters

Converters which use valves without turn-off capability need to be equipped with a capacitor for generating an “artificial” commutation voltage to advance the firing. Such circuits are more complex, have limited operating area and impose higher costs because of more components involved.

Using forced commutated converters that employ gate–turn-off (GTO) or insulated gate bipolar transistors (IGBT) makes it possible for a converter to operate in four quadrants (Section 2.5). As the switches of the CSC should conduct current in only one direction but maintain voltage in both directions, they must use forced-commutating devices that can block voltage in both directions. In Figure 1.3, a GTO-based forced commutated VSC is shown.

Using capacitors between the phases on the ac side facilitates commutation of the current but as these capacitors are normally large, the cost will increase. Another drawback of such topology is that with the converter being of current-source type, it is not possible to control the reactive power independently of the active power. Also the valves are stressed with the high over-voltages in both forward and reverse directions.

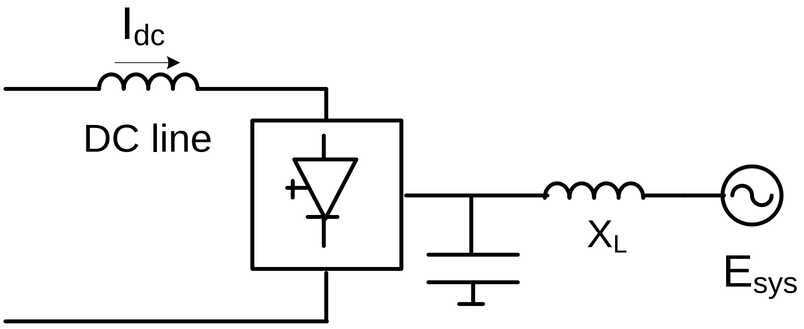

Figure 1.3 Forced-commutated current-sourced converter using GTO valves

These types of converters have been used for lower levels of power in dc transmission in recent years; they are also used for traction applications and motor drives. Such converters have specifications such as independent control systems on rectifier and having reduced risk of commutation failures, no dependency on a telecommunication connection, improved speed and the reliability of the controller. On the other hand VSC is sensitive to dc-side faults, it has considerable power losses due to high frequency switching, and is not available at high power/voltages [6]. The switches mostly used today are a combination of IGBT and reverse diodes. A simple schematic of a forced commutated IGBT-based VSC is shown in Figure 1.4.

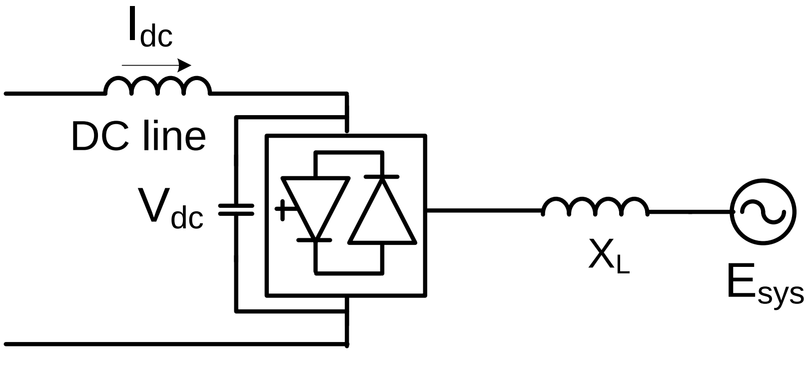

Figure 1.4 Forced commutated VSC using IGBT valves

1.4.3 Advantages and disadvantages of LCC and VSC converters

Line commutated converters have been the most common option for HVdc applications. They are inexpensive and commercially available in higher ratings. Also by reversing the voltage polarity of these converters, the direction of power flow can be changed. For some applications such as cable transmission and multi-terminal systems connected in parallel on the dc-side, in which operation with a constant voltage is desirable, this feature of LCC is a disadvantage.

In LCC converters, the ac current always lags the line voltage, due to the firing delay on the thyristors. This means that they always need to consume reactive power, which is a disadvantage. This reactive power must be provided through var generating devices connected to the ac work. If such converters supply a very weak electrical system, severe problems might develop. One consequence of connection to weak ac networks is that because such converters rely on the line voltage for commutation, if a major disturbance happens in the ac voltage, it might cause repeated commutation failures.

On the other hand, using forced-commutated converters and applying pulse width modulation (PWM), it is possible to control the active and reactive power both continuously and independently (Section 2.5). Such converters are capable of both generating and absorbing reactive power. Another advantage for these converters is that there is not a danger of commutation failure. Because of this, forced commutated VSCs are less sensitive to ac voltage variations/disturbances. Such converters are capable of controlling the frequency of the ac system, the active power and the ac system voltage. Also because the direction of the real power flow can be reversed by changing the direction of the direct current, the VSC-based converters can be used for cable transmission system, which might need a rigid direct voltage.

One major disadvantage of VSC converters is that a fault on the dc-side will generate high over-current which cannot be limited using system controls and lowering the dc voltage level. Other disadvantages are high losses, their high cost and their general unavailability for ratings above 500 MW.

1.5 What is a hybrid converter and why use it

This thesis introduces the concept of a hybrid converter. Hybrid converter is a converter that can appear with either series, or parallel arrangement of LCC, and VSC converters. LCC is the building block of commonly-used HVdc schemes and works well in strong ac systems. However in weak ac systems it demonstrate very slow recovery rate after fault, and sometimes it may not recover at all and require converter blocking and restarting. Under very weak ac system conditions, the ac system may not be able to attain a steady state operating point at all. Understanding that each of the LCC / VSC converter systems has their own points of strength/weakness, there is the possibility of assembling a composite converter system based on these two types of converters that possesses the most of advantages of these two kinds of converters, while minimizing the disadvantages of each.

Hybrid converters may have different structures and have their own limitations. At the converter level, different hybrid configurations such as series and/or parallel combination of LCC and VSCs might be constructed. Other more complicated configurations for hybrid converter HVdc transmission systems are also possible but these configurations come with more complex circuits/controls and higher expenses, which makes their technical or financial justifications difficult. In this thesis two separate configurations of series and parallel hybrid converters, each consisting of one current, and one voltage sourced converter has been studied in detail. Out of these two the series hybrid option case was found to be promising. More details are given in Chapter 3.

1.5.1 The benefits of hybrid converters

An ideal HVdc converter should permit operation at full power range at any desired power factor including import/export of reactive power, eliminate commutation failure issues in severe faults (if possible), causing no significant amount of harmonic, and have low losses. Hybrid HVdc, which employs conventional and newer HVdc technology together, is a move in this direction. Using a well-designed “hybrid” converter, some of the weaknesses of the LCCs will be overcome by VSC characteristics. These include:
(i) the need for external reactive resources will be eliminated; (ii) a large part of filtration would be un-necessary; (iii) stronger inverter voltage support will be provided; (iv) real and reactive parts still may be controlled independently to a good extent (though it will not be necessary to control the reactive power any more), and (v) the terminal voltage will be controlled.

At the same time some of the weaknesses of the VSC will be improved by conventional HVdc system, including lower rating of VSC will be compensated using higher assigned share of power to LCC; less switching losses because of lower power share of VSC converter.

1.6 Scope of the work

In this report the feasibility of employing two configurations of VSC-LCC hybrid-converter HVdc transmission systems connected to a very weak ac system are studied and the benefits expected from employing such topologies in comparison to a LCC-only, or to a VSC-only based HVdc transmission system are stressed. The overall hybrid systems' behavior during start-up, steady-state, and following small and large dynamic changes has been studied closely.

To fully investigate the behavior and performance of the proposed hybrid HVdc transmission systems a coherent and exact mathematical model of both of its constituent converters, namely the LCC and VSC converters, is needed. In fact the complexity of the complete converter system and extensiveness of the integrated model prevents one from mathematically analyzing the complete HVdc system. The difficulties and complexities associated with such a model may be summarized as follows:

- Extensiveness of the system,
- Discontinuous and non-linear nature of signal transfer through converters,
- Frequency conversion through ac-dc converters,
- Complexity of interactions between ac and dc variables,

If performing an exact mathematical-based analysis is not possible, a simulation-based method can be used instead [11]; also from an engineering point of view, more familiar physical results could be expected from time domain simulations. A number of the expected advantages from simulation-based studies are:

- Ability to reproduce system performance with highest realistic degree of complexity that is desired,

- Investigating system fault modes and predicting the important parameters such as over-voltage and over-current stresses on energy storage elements and also on switching elements at system, and at component-level,
- Having a “visual image” of system behavior under different working conditions,
- Having a realistic estimate on recovery time for an HVdc system, following disturbances with different types and severities,
- Providing the basis for protection requirements in a real HVdc system.

The PSCAD / EMTDC software [12] was selected for simulating the system and studying its behavior, as this tool is particularly suited for modelling of power electronic-based electrical networks. The results obtained from simulation will be presented in Chapter 4.

1.7 Objectives of the work

The objectives of the research are summarized as:

- Introducing the series and parallel hybrid configurations at the converter-level and assessing their strengths/weaknesses in an HVdc transmission system;
    - Analyzing and evaluating the series and parallel hybrid converter behavior following small and large dynamic changes in the electrical system;
    - Examining the idea of using series and parallel hybrid converters in a very low SCR system;
- Optimally designing and simulating the series and parallel hybrid converters
- Performing detailed hybrid system performance comparison with an LCC-only (conventional) HVdc;
- Suggesting and discussing the series and parallel hybrid converters’ applications.

The thesis concludes that the SHC configuration is a promising option for providing real power to a very weak ac electrical network, while adjusting the terminal voltage at specified limits. It also concludes that the PHC option is not a good candidate for working under very low short circuit ratio conditions and does not demonstrate an overall good dynamic performance. It also suffers from an intrinsic drawback, to be discussed later (Section 4.9).

1.8 Thesis outline

Following the introduction given in this chapter, the rest of the thesis is organized as follows.

Chapter 2 presents the basic operational principles and control strategies of LCC-HVdc, and VSC-HVdc systems, in parallel.

In Chapter 3, the hybrid concept is detailed and different hybrid configurations at system and at converter level are covered. A series, and a parallel hybrid converter HVdc system will be designed and its details will be worked out. The control methods are also elaborated.

In Chapter 4 the results of detailed digital simulation of the hybrid system using PSCAD/EMTDC simulator is presented. The system steady-state and dynamic behavior of the system will also be discussed.

In Chapter 5 the hybrid converter’s applications and the highlights of performed tasks is discussed. Then conclusions obtained from the research and contributions of the work are presented. Some suggestion/ recommendations for continuing the work are also offered.

A list of references will be presented afterwards and Appendices will provide more detailed information regarding system design and some of its numerical figures and parameters.

1.9 Literature review

Building blocks of HVdc converters usually use line-, or forced commutated type of semiconductors [13].

Thyristor-based (LCC) HVdc transmission systems have advantages over HVac systems and it validates their common usage around the world [14], such as: ability to work between non-synchronous ac systems, carrying more power per conductor, being more economical at high power / long distances and less corona losses [15], and having good reliability [16].

On the other hand they have disadvantages such as need for large reactive power and filtration [4]; experiencing difficulties in working with weak ac systems at normal conditions, such as commutation failure [2], slow fault recovery, high over-voltage following load rejection [3], second harmonic resonance [17], [18], [19], voltage/power instability problems [19]-[20], inefficient real power modulation to control power system dynamic [21].

Direct current transmission utilizing LCC converters is not a new concept and because of the large number of HVdc transmission systems of this type; they have well established basis in different aspects such as modeling, control, protection and standards [1],[4]-[5]. Development of the Cigré Benchmark model [22] is an important step in CSC-HVdc modeling. Despite the maturity of these converters, there are categories with on-going research subjects such as modeling and control for different types of HVdc transmission systems, based on conventional or hybrid converters.

The main operating problems with the conventional HVdc systems connected to weak ac systems are the high-magnitude ac voltage oscillations and the difficulty in recovery from disturbances [2], [9] and [23].

The ability of operating these type of converters under very weak SCRs is highly questionable [3], [8]. Modifications on standard control methods have also been proposed that work for very low SCRs but fail for SCRs as low as one [24]. The dynamic instabilities caused by the weak receiving ac systems are described in [25]. The dynamic performance of a STATCOM, making emphasis on voltage stability, over voltages and post fault recovery for a specific system of SCR = 1.5 offers the best and fastest results in comparison to isolated solutions using dynamic var generator equipments such as synchronous condensers and static VAR compensators [9], [10] and [26].

Theoretically, VSC-HVdc systems using forced commutating devices are not a new concept either [27]. These systems use devices such as IGBT/GTO semiconductors [28]-[29]. These systems have advantages compared to conventional systems (see Chapter 2 for more details). VSC converters have overcome some of the difficulties that current-sourced LCC-HVdc transmission systems have, such as difficulty in working with very weak ac systems, not relying on external reactive power sources, etc (Chapter 2) VSC applications in HVdc transmission systems come in different topologies and control schemes [6] and may even supply passive networks [30], but currently there are few real high power applications for them [31].

VSC-HVdc is less mature than conventional HVdc systems but the technology based on these converters is mostly commercially available as HVdc light (plus) [32], [33]. Different aspects of VSC-HVdc have been collectively addressed in [6]. Some specific aspects of these converters have been addressed in other publications such as system-related issues [34], [35], [36], analysis and modeling [37], [38], [39], [40], [41], design [42],[43] , control and protection [44], [45], and applications [46].

In this thesis, both hybrid and non-hybrid HVdc transmission systems are categorized. These depend on the level (transmission level vs. converter level) , type of commutation (LCC vs. VSC), type of converter (LCC vs. VSC), and a mixture of the level, commutation and converter type.

Based on the level, the configuration might be:

- at transmission level, which includes:
    - type of commutation (non-hybrid systems, with LCC or VSC in both sides; and hybrid systems, with LCC in one side, VSC on the other side)
    - type of converter (non-hybrid systems, with LCC or VSC on both sides; hybrid systems, with LCC in one side, VSC on the other side)
- at converter level, which includes:
    - type of commutation (non-hybrid systems, with only LCC or VSC in a converter; hybrid systems, with both LCC and VSC in a converter, or two different VSC types in one converter)
    - type of converter (non-hybrid systems, with only LCC, or VSC type; hybrid systems, with both of LCC and VSC types).

In recent times the most common configuration for HVdc transmission has been non-hybrid at transmission level (Chapter 2). This scheme, which is of current-sourced LCC type, is an HVdc system with the same converter configuration at both sides, a well-known example of which is Manitoba's HVdc transmission system. A counterpart for this scheme is the non-hybrid, VSC-HVdc system, which has started gaining more popularity in recent years because of availability of newer and more powerful self-commutating semiconductor switches. Such systems have various applications in large industrial power systems [47], as an example.

The schemes that use non-conventional converters on both sides are non-conventional HVdc systems at the transmission level.

The schemes that come with different converter configurations on the rectifier and inverter sides (LCC-VSC HVdc), but use simple (non-composite) converter structures at converter level, may be named "simple" or "basic' hybrid schemes at transmission level. There are hybrid schemes at transmission level:

- A "basic" hybrid HVdc transmission system has LCC at the rectifier side and one VSC at the inverter side, feeding a weak ac system, but the converter is not a hybrid one [48]. It should be noted that the earlier research also refers to "hybrid", but in a different sense.
- A laboratory-scaled prototype for 300 MW back-to-back GTO based HVdc transmission system was developed which is a LCC-VSC HVdc system [50]. Another GTO-VSC-based system may be found in [51].
- Different transmission-level hybrid configurations have been compared in [52].

Other proposed non-conventional arrangements include modified thyristor based converters are as follows:

- The Capacitor Commutated Converters (CCC), introduced in 50s, which is an improvement in the thyristor-based commutation [53]. This type of converter appears much less dependent on the ac network strength and the capacitors used in series connection to the converter, improves the commutation failure performance of the converters when connected to weak networks [54][55], [56]. To completely eliminate commutation failure, however, very large series capacitors are needed, which increases voltage stress and demands higher insulation level for series commutating capacitors and generates more dc harmonics. It also consumes very little reactive power (around 10%–15% of converter power rating).
- The combination of a CCC and a STATCOM for voltage support and a passive filter was suggested for use in an offshore system [62]. Here the STATCOM may be of very short term help as a voltage support for the receiving end system. The disadvantages of the use of synchronous condensers in term of slow responses and high losses are discussed in [63]; they also become less effective when ac voltage level is reduced.
- The Controlled Series Capacitor Converter (CSCC) [57], which is a combination of a Thyristor Controlled Series Capacitor (TCSC) and LCC-HVdc. In comparison to CCC, it has smaller valve ratings and smaller harmonics but has larger valve short circuit currents; this current is still smaller than conventional

converters current. This hybrid converter fits in the category of artificially commutated converters.

Schemes with more than one type of converter at one side, configurationally similar to the proposed ones, are listed below:

- In [58] an HVdc system is proposed which consists of a series connection of one conventional LCC, and one VSC converter. In this design, the conventional converter generates all the active power needed, while the proposed VSC converter has only been used as an active filter to lower the total harmonic content of the HVdc transmission system and not for power transfer purposes [59]. In ref [60] a VSC-based STATCOM has been used to support inverter terminal voltage of an HVdc system connected to the inverter side of a very weak ac systems with SCR lower than 1.5. Again the VSC part is not supporting real power generation. In this design over-voltages are noticeable following three-phase faults on ac-inverter terminal.
- In [61] the possibility of using a converter with two different types of forced commutating device converters (IGBT and GTO based converters) to establish a high voltage / high efficiency converter system having virtually harmonic-free input/output has been proposed.
- Conventional LCC converters of mixed type, with one rectifier and one inverter connected through impedance in one side, and connected to different dc systems on the other side have also been suggested [64].

The idea of using a series or a parallel LCC-VSC hybrid HVdc transmission system at converter level (hybrid converters in inverter side, or hybrid inverters) with real power generation assistance from the VSC converter has never been proposed before. In both of the series and parallel converter options both of the two converters generate their share of real power, as per design, to feed a very week ac system. These options employ the robustness of a LCC converter and at the same time use the dynamic voltage support and general higher fault immunity of a VSC converter in one integrated hybrid design.

It is possible to have hybrid converters at different levels at the same time. For example there are recent applications for parallel HVdc transmission systems that use different types of converters on different transmission lines ending to a point of common coupling (such as one LCC converter in one line, and one VSC in another line in an HVdc transmission system).

Chapter 2: LCC vs. VSC Based HVdc Transmission Systems

2.1 Introduction

In this chapter the main components of current- and voltage-sourced converter-based HVdc transmission systems are introduced. The chapter starts with the major semiconductor components used; continuing with main system components and detailing the control methods and levels of controls. Along with the parallel representation of these two types of converters, the Cigré Benchmark model will also be presented [22].

2.2 HVdc system requirements and characteristics

Today there is an increasing requirement for feeding very weak ac systems, i.e. the ac systems having high impedance or inadequate inertia. For such applications it is of great importance to be able to operate over the entire real power range with minimum impact on the voltage of the ac network. This requires coordination of the HVdc and reactive power support. Supplying power systems without local power generation, i.e. dead ac networks, are also possible; it has been accomplished using frequency control method of the islanded network [62].

An HVdc system has some requirements that must generally be met [1]:

- First, low costs, which is mainly determined by the cost of transformers, valves, filters and capacitor banks; second, engineering and control equipment, which are subject to constant changes, e.g. size of the reactive power generation devices can be reduced if the converters are able to both consume and generate reactive power, third, cost of the valves which is closely related to the semiconductor technology development.

- Low losses
- High reliability and availability
- Possibility to quickly control of the active power flow, ac and dc voltages
- Satisfactory operation at disturbances, or having low risk for commutation failures and ability to control fault currents on the dc side
- Low harmonic generation
- Polarity changes, which means that a stiff dc voltage is required
- Low disturbance, in case of multi-terminal systems

2.3 HVdc system components and their representation

2.3.1 Converter building blocks

Power electronic converters are building block devices that deal with the conversion and control of electric power by supplying voltage and current. To achieve any conversion between ac and dc a “valve” has to be used, which might consist of line-commutating (such as thyristor), or self-commutating semiconductor devices (IGBT, GTO, etc.).

2.3.1.1 Thyristors

Thyristor may be thought of as an equivalent of a controllable “current valve” with two discrete states that might be in conducting or blocking state of the current. To turn on a thyristor a short-duration positive current pulse has to be applied to the gate, provided that the device is in forward-blocking state. After turning on, it conducts as a diode and gate signal may be removed. Thyristor cannot be made to turn off by pulse application. To turn it off, the current passing through the device should have a “zero-crossing”. Currently the most powerful thyristors can handle the voltages/currents at the level of 8-10 kV/3-4 kA. They may be connected in series or parallel, to suit a specific voltage / current / power application. At the highest level of power still there is no practical substitute for this device. They have very low conduction, and switching losses. Thyristor symbol and its *I-V* characteristics may be seen in Figure 2.1, [65].

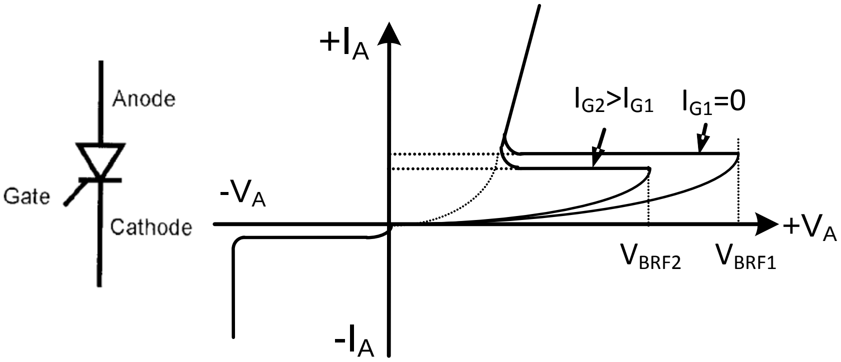

Figure 2.1 Thyristor symbol and its I-V characteristics

2.3.1.2 Gate Turn-Off Thyristor (GTO)

A GTO, similar to a thyristor, has switch-like characteristics. It may be turned on by a short-duration gate current pulse. Once in the on-state, it may stay on without any further gate current. But unlike thyristors, it can be turned off by applying a negative gate-cathode voltage. This pulse may be very short (a few micro-seconds), but must have a very large magnitude (as large as one third the anode current). A GTO has high power losses and usually needs an extra protection circuit. GTO symbol and its *I-V* characteristics may be seen in Figure 2.2, [65].

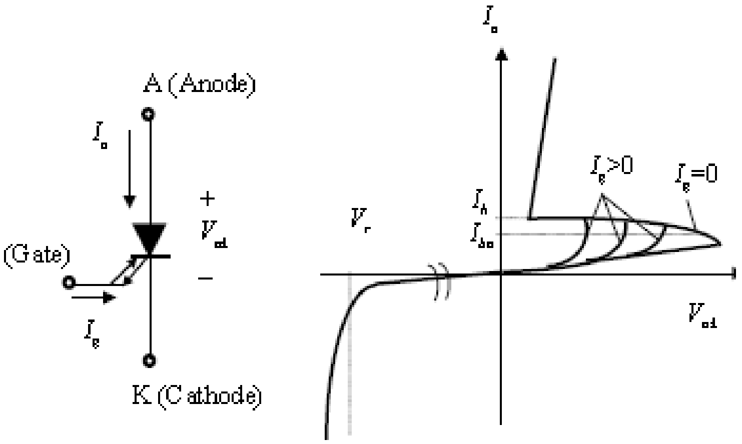

Figure 2.2 GTO symbol and its I-V characteristics

2.3.1.3 Insulated Gate Bipolar Transistor (IGBT)

IGBT component operates based on bipolar transistor concept. Using small amounts of power supplied to the control gate, the current flowing through the device may be controlled. IGBT can handle external fault conditions, using the bipolar effect that limits the current passing through it. The device may be protected by turning it off in a few micro-seconds.

In forced commutated converters an IGBT switch is used in forward direction, which might be turned on and off. Also there is usually an anti-parallel free-wheeling diode (FWD) integrated on the same package to ensure current flowing in the opposite direction, and also to prevent from reverse voltage across IGBT. Today’s voltage and current rating of IGBTs are around 6.5 kV/2.5 kA. Using SiC-based IGBTs instead of usual silicon-based ones, the device voltage rating may be doubled or even tripled [66]. They have higher conduction losses and switching frequency-dependent losses than can vary based on the converter topology and modulation method employed. IGBT symbol and its $I-V$ characteristics may be seen in Figure 2.3, [65].

2.4 LCC-HVdc systems and their basic principles

Thyristor-based HVdc transmission systems have advantages over HVac systems (Section 1.4.3). In these converters the commutation relies on the existence of an ac voltage source. Due to the presence of the reactance (the leakage inductance of the converter transformer), the current phase angle always lags the voltage phase angle and the converter always has to absorb significant amount of reactive power, which is around 60% of the power rating of the converter [4]. In other words, both the rectifier and the inverter consume variable reactive power, which must be supplied by the network and/or by other reactive power resources (shunt capacitors, ac filter switching, etc.) which are connected to the point of common coupling (PCC). A simplified representation of an HVdc system using LCC converters has been shown in Figure 2.4.

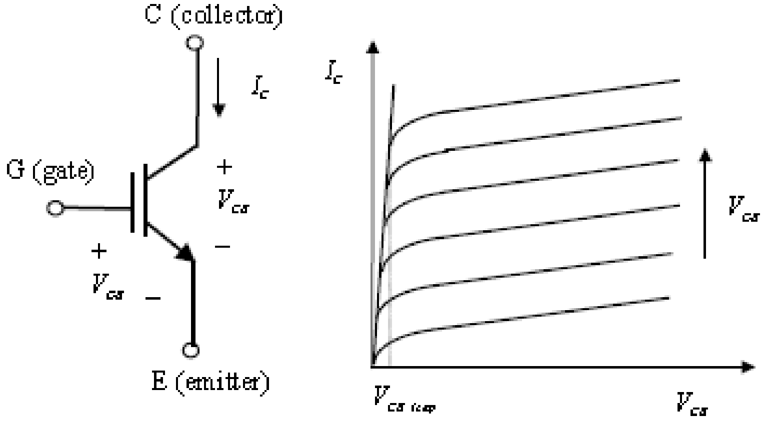

Figure 2.3 IGBT symbol and its I-V characteristics

In the LCC theory it is usually assumed that the dc current is a non-zero constant, which always has to be higher than a minimum level; the ac system is electrically strong,

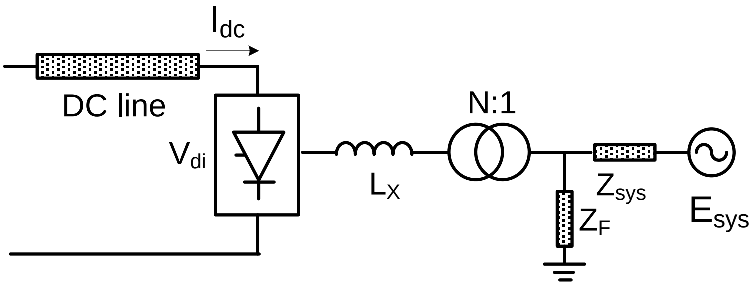

Figure 2.4 A simplified HVdc system with line commutated CSC at inverter side

and its electronic switches are assumed to be ideal [4]. Several problems may occur if the ac system is not sufficiently strong or the rate of the transmitted power is high, relative to the short circuit capacity of the ac system.

The dynamic instabilities caused by the weak receiving ac systems manifest themselves as the high-magnitude ac voltage oscillations and the difficulty in recovery from disturbances. These two can be regarded as the most important factors in limiting the use of HVdc power transfer technology to the weak ac systems using conventional LCC technology, both in number and in capacity [25], [67]. In this thesis it is shown that one of the strength points of a VSC-LCC hybrid HVdc scheme is that they do not suffer from such difficulties.

For the inverter operation, the turn-off time of the thyristors dictates a minimum extinction angle of typically $15-18^\circ$ to prevent a commutation failure, which adds to the reactive power consumption in a LCC [4]. As the reactive power used by LCC varies with load, usually a number of (switch-able) filters and shunt capacitors are used in these systems. Filters will also limit the amount of harmonics to the level required by the standards [68]. LCC's reactive power absorption needs can be controlled through turning on/off of harmonics filters / capacitors.

In many HVdc systems with low SCR the ac voltage fluctuations, even without actual instability, can be harmful for ac equipment, and so the quality of power supply and the probability of commutation failure will increase on the dc side. Consequently the link rating is determined on the basis of minimum safe SCR. Also an active power change causes an equivalent reactive power change, resulting in an ac system voltage fluctuation. The recommendation is that for successful conventional LCC operation, the strength of connected ac systems should be greater than 2.0 [69]; part of this restriction is because of the conventional operation modes of LCC converter controls.

The weaker the ac system (i.e. the lower the ratio of the short circuit capacity of the ac system to the dc link power) is, the greater the undesirable effects and the ac/dc interaction phenomena [5]. The problems associated with the interaction between HVdc schemes and weak ac systems can be found in [8], [9], [10], [69], [70], [71]. The difficulty of providing the voltage support to alleviate some of the difficulties related to operation under weak ac systems using different types of compensators has been reported in [9], where the studied system has the SCR = 1.5. Some of the problems associated with weak ac systems are: high temporary over voltages, e.g. at load rejection [58], [71]; low resonant frequency [58]; long clearing time after a fault [71]; voltage / power instability [20]; core saturation instability[17], [20], [72]; harmonic generation/frequency instability [71], [72], [73]. The frequency instability is a result of low inertia in the ac system. Installation of large synchronous machines increases the inertia and stabilizes the frequency. A combination of the second harmonic parallel resonance on the ac side and a fundamental frequency resonance on the dc side can result in core saturation instability [9], [10].

The maximum available power (MAP) from a dc link feeding power into an ac system is affected by the SCR, the transformer reactance, minimum extinction angle (γ), system damping, the shunt capacitors and the ac filters [74]. Increasing I_{dc} beyond the MAP point causes lower real power generation and demands more reactive power; it finally causes ac voltage collapse. The weaker the ac system (the smaller the SCR), the smaller the MAP peak and the faster the ac voltage will drop.

In conventional LCC converters, the dc line power flow can be controlled by controlling the dc voltage at the receiving-end converter (inverter) at a constant value, and by letting the sending-end converter (the rectifier) control the dc current. In these systems it is not possible to change the direction of dc current. To change the power flow direction, the dc voltage polarity of transmission line must change.

The highest rating for an LCC converter has 6400 MW, ± 800 kV dc voltage, which is under construction [75].

2.5 VSC-HVdc systems and their basic principles

Forced commutated semiconductor devices such as GTO (Section 2.3.1.2) or IGBT (Section 2.3.1.3) are used as the main switching device in a VSC converter. These devices have the ability of tuning off the current by applying a negative signal to the device’s gate. Adding an anti-parallel diode to the device lets the current flow in both directions, so the device must be designed to maintain only forward blocking voltage. For square wave operation, each valve in a leg conducts current during only one-half cycle, which means that each phase is connected to the positive pole during one half cycle and is connected to the negative pole during the other half of the cycle. In order to have a symmetric three-phase system it is required that components turn on at 120° intervals from each other.

It is possible to refer all of the potentials to a virtual midpoint on the dc side. Potentials at each leg of the converter can be written based on differences in line voltages, this way the potential of the neutral point of the secondary of the transformer would be a square wave. VSC generates its own voltage source with controlled amplitude and phase angle. This is the most important difference between a LCC and a VSC in HVdc transmission systems. The capacitor on the dc side and the reactor on the ac side are major components for VSC operation. A simplified representation of a VSC-VSC HVdc system is shown in Figure 2.5.

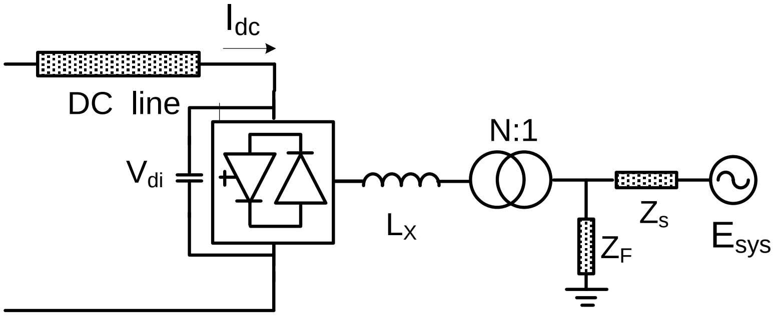

Figure 2.5 A simplified HVdc system with forced commutated VSC converter

Figure 2.6(a) shows the basis for VSC operation. By turning on and off of the forced commutating switches, a fundamental frequency ac voltage is generated at the converter side (V_{cnv}), and a smoother ac voltage (dashed line) is generated on system side (Figure 2-6(b)). The VSC's capacitor is normally used for smoothing the dc voltage [76]. The converter (interface) transformer is mostly used for providing a reactance between ac system and converter unit, and matching VSC's ac output voltage with ac system voltage.

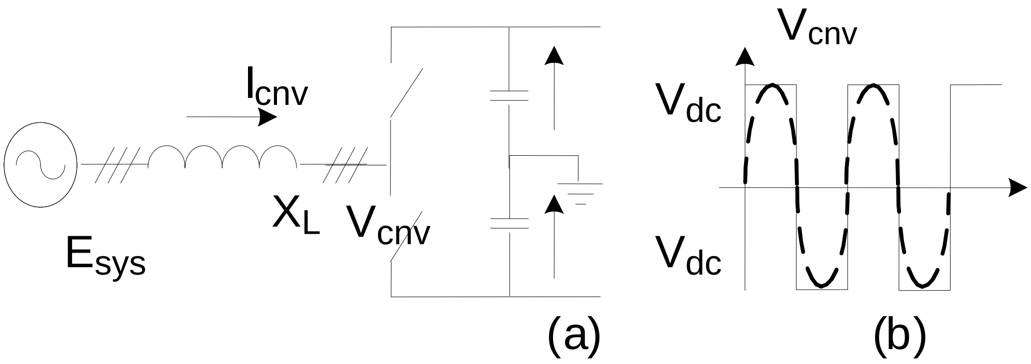

Figure 2.6 (a) Principle of VSC operation, and (b) generated ac voltage waveforms

The VSC's output voltage should be connected in series with a phase reactor to control the power flow, and to smooth the output current. The amount of filtering in VSC-based converters is much less compared to line (natural) commutated converters. The common switching component used today is IGBT in a 2-level configuration. Adding more components in series connection, increases dc-voltage handling in a fairly straightforward manner. Current handling may be improved by increasing semiconductor active area in the IGBT-modules, improving cooling and optimizing the switching process.

The direction of the reactive power flow is determined by the difference (ΔV) between the system ac voltage (E_{sys}) and the converter voltage (V_{cnv}), shown in Figure 2.7(a). Direction of the real power flow is determined by the phase difference (ϕ) between the fundamental frequencies of the voltages, shown in Figure 2.7(b). These features permit the independent control, and generation/consumption of active and reactive. This is a major advantage of the VSC converters, compared to conventional LCC converters. In VSC converters, the maximum reactive power generation capability is less than active power generation.

The direction of the dc current can be controlled using the control of the firing angle. A disadvantage of the VSC converters is its inability to reduce the dc current and by that reduce the dc current by the firing control at dc line to earth faults.

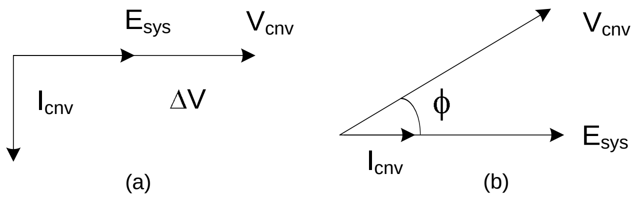

Figure 2.7 (a) Reactive, and (b) active power generation in VSC converters

VSC converters have advantages compared to conventional LCC converter systems [47]: possibility of independent control of active and reactive power; ability to rapidly control both the active and reactive power; ability to operate into very weak and dead systems; ability to provide reactive power and voltage support, employing pulse-width modulation (PWM) to limit lower order harmonics; the ability to work under any level of dc current; having no contribution to short circuit currents [77]. The maximum active power that can be provided for the ac system is the reciprocal of the impedance of the ac system (in p.u.) as seen from the VSC's ac terminals [3]. VSC does not have any limit on the SCR for stable operation, but the amount of reactive power transfer is limited to the ac system impedance in accordance to the normal ac system theory, and VSC's transformer power rating.

On the other hand VSC converters have disadvantages: being sensitive to dc-side faults; having generally higher power losses due to the high frequency switching; smaller ratings in comparison to conventional converters; and general unavailability at high power/voltages [78].

The largest VSC-HVdc converter valves (as of 2010) based on IGBTs has the power rating of 400 MW, voltage rating of ± 200 kV and maximum dc current of 1050 A [79]. Increasing the valve switching voltage leads to higher influence of stray capacitances. The challenge in increasing the dc voltage to levels as high as ± 300kV is to achieve sufficient voltage sharing between the series-connected IGBT components in both switching, and blocking conditions. Lowest valve cost per MW is achieved at maximum ac-current. The main limiting factors here are maximum semiconductor temperature and switching capability of the IGBT module. The temperature of the IGBT is largely governed by the losses generated, which come from two main contributors of conduction and switching. As semiconductor technology advances, conduction losses are being lowered continuously. Switching losses generally depend more on the converter topology. The switching frequency then determines the average switching losses. A low switching frequency reduces the power dissipation but it also affects the controllability of the converter so there is a trade-off between them. Increased current handling of IGBTs may be reached by optimizing the switching pattern and improving the heat sink.

The quality of the output voltage can be improved using the Pulse Width Modulation (PWM) method [65]. In the most straightforward implementation, generation of the desired output voltage is achieved by comparing the desired reference waveform (modulating signal) with a high-frequency triangular ‘carrier’ wave (Figure 2.8).

In this method, when the modulating (reference) signal is larger (smaller) than the carrier waveform, the output voltage is switched to its high (low) state. Using this method, it is possible to vary the ratio between the fundamental value of actual component of the converter output voltage and of the un-modulated output voltage of the converter (voltage at square wave operation). The ratio of A_m (maximum value for modulating signal) over A_C (maximum value for carrier signal) is called modulation index (m, or MI). Controlling the modulation index therefore controls the amplitude of the applied output voltage.

PWM shifts the first characteristic harmonics towards higher frequencies, making it possible to control the output voltage magnitude and the VSC harmonic content. Depending on the application the VSC switches usually operate at 5-30 times the power frequency [6]. As increasing the switching frequency causes higher switching losses, an -

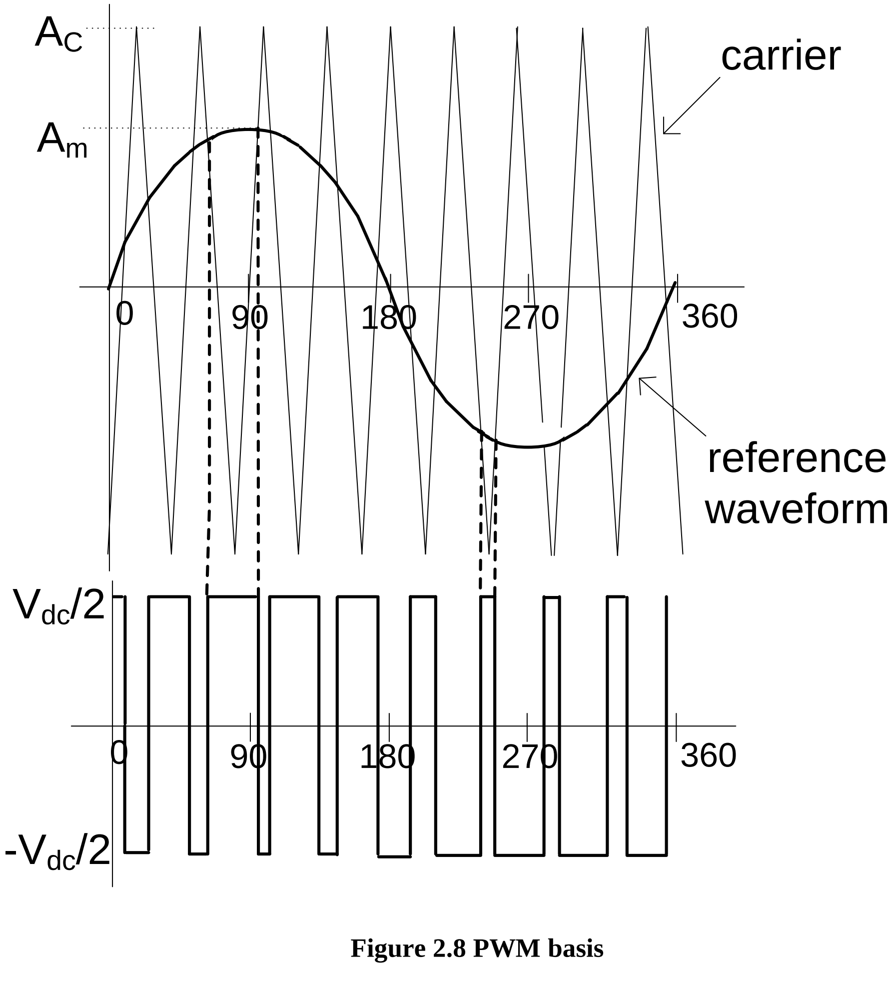

Figure 2.8 PWM basis

optimization algorithm/method can be used to balance the harmonic level on one hand, and parameters such as power losses, on the other hand. In this research, the Sinusoidal Pulse Width Modulation (SPWM) has been used [82].

2.6 Converter arrangements

2.6.1 Arrangements for LCC-HVdc schemes

The thyristors of LCC may be configured as series/parallel, and in 6/12-pulse converter configurations. They might also come with multi-tap inter-phase reactors. The HVdc link itself may be classified into mono-, bi-, or homo-polar link categories [80]. Standard LCC-HVdc systems may be put into service in different ways:

- Back-to-Back scheme, with two ac systems physically located in the same place,
- Point-to-Point scheme, to transfer electric power through dc transmission or cables between two geographical locations,
- Multi-Terminal scheme, in which three or more geographically separated HVdc substations connected either in series or parallel configurations to each other,
- Unit Connection scheme, in which a dc transmission is applied at the point of generation to the converter transformer of rectifier.

With current technology of ± 800 kV dc transmission lines, series / parallel connected 12-pulse groups can deliver electrical power of around 7200 MW [75].

2.6.2 Arrangements for VSC-HVdc schemes

The desired output waveform of a VSC is a good approximation of a sine-wave, which may be constructed using different methods [14]. The converters can be arranged in different topologies, with varying number of dc voltage levels, inputs/outputs and different levels of complexity in their switching patterns [6]. By combining the 2-, 3- or multi-level phase unit topologies for converters the 2-, 3-, or multi-level (6-, 12- or n-pulse) converter systems are created accordingly [73]. Combining the output from several phase units and/or repeatedly switching the valves will help in reducing the harmonics [26]. If the number of pulses is higher, the converter will be bigger, more expensive and must use more complicated control methods. Converters may be connected in series, parallel, or both, at dc terminals; and series or parallel at ac terminals of the converter units [6].

In a 2-level phase unit, PWM technique brings the possibility of direct control on the fundamental magnitude of the output voltage amplitude [80]. The switching may also be arranged to cancel out the characteristic harmonics using Selective Harmonic Elimination Method (SHEM) [81].

2.7 HVdc controls

2.7.1 LCC controls

Earlier HVdc schemes used individual phase control systems, where the firing instants were determined individually for each valve. Using equi-distant firing control the time interval between valve firings would be equal, and matches an angle of $60°$.Individual phase control method results in different time intervals between the firings, and generates higher non-characteristic harmonic contents. In practice, control blocks such as VDCOL (Voltage Dependent Current Order Limiter) are needed to reduce the current order at large reductions of the dc voltage.

The control system in an LCC-HVdc system attempts to maintain constant dc current and voltage in the dc line. In practice, the rectifier usually sets the dc current and the inverter sets the dc voltage. Then the current error is measured, amplified and filtered. Based on the output signal, pulses will be generated at certain times for equi-distant firing. These pulses must be converted to valve firing pulses. Current-control is generally required to have a quick response, while voltage-control has a comparably slower response to avoid unstable control interaction [4].

The LCC has different control modes. The preferred modes of control are:

- The inverter controls the dc voltage, under steady state conditions, by maintaining a constant extinction angle which causes the dc voltage to drop with increasing dc current. As the ac system gets weaker, the droop will be steeper.
- The inverter can operate in a dc-voltage controlling mode, which demands the extinction angle (γ) to increase beyond its minimum setting. As long as the delay angle (α) is not at its minimum limit (usually $5°$), the rectifier must control the dc current if the inverter is operating in a minimum constant-γ or constant-voltage characteristic. If the system controls do not have a constant dc voltage-control, the γ–control and the tap changer will provide the dc voltage control.

By selecting the minimum value among the outputs of constant-current, voltage, and extinction angle controls, a control characteristic is achieved. In order to have a stable dc current-control the dc current order of the inverter has to be smaller than that of the rectifier by the current margin, the intersection of them indicates the steady-state (operating point) of the LCC. Different features of classical modified LCC control are drawn in Figure 2.9 [5].

2.7.2 VSC controls

The VSC has the following main control levels [6]:

- System control that enables the VSC to perform major system functions (voltage magnitude control, etc.)
- Converter unit control (sending power into, or out of the converter, etc., through controlling both the phase angle and the voltage magnitude)

In a VSC-HVdc system the valves will generate a fundamental frequency (f_0) ac voltage from a dc voltage, in which the magnitude and phase of the f_0 component of that ac voltage has to be controlled. Common controls are based on the two signals of Modulation Index (MI) and Phase Shifting (PS) signal (Figure 2.8), [6].

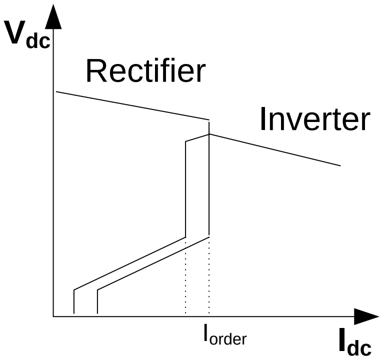

Figure 2.9 LCC control features

The MI is defined as the ratio of the desired fundamental frequency component of ac voltage magnitude (to be generated by the VSC), to the maximum possible ac voltage that could be generated (which is a function of the dc side capacitor itself) and is limited between 0 and 1.

The PS is a signal generated through the phase shifting of the fundamental frequency ac voltage with respect to the phase locked loop (PLL) block, which is normally synchronized to the voltage.

Controlling the MI and PS for VSC-HVdc transmission applications is usually achieved by either:

- Direct control, in which the MI or PA will be directly adjusted by the parameters being controlled, using the error signals as inputs to controllers,
- Vector control (also known as decoupled control), which is a current control strategy that decouples the adjusting action of the MI from the PS, [84].

The decoupled control is the conventional mode for VSC-HVdc converters and is discussed later (Section 3.12.1).

In the direct control method the voltage magnitude may be controlled using MI. When the voltage magnitude is greater than the voltage the reactive power will be transferred into the ac side, which is similar to an over-excited synchronous generator, and vice-versa.

In VSC-HVdc schemes, different control methods/modes can be used:

- Ac voltage-control method, where the magnitude of the fundamental frequency component of the ac voltage error, generates the phase-angle (ϕ) control signal
- Power-control method, where the phase-angle error between fundamental frequency component of ac voltage at the converter side, generates the signal for phase-angle (ϕ) control
- Reactive power-control mode, where other controllers act to maintain ac voltage
- Dc voltage-control mode, where active power can be regulated through controlling the capacitor voltage

- Current-control method, which is part of the vector control itself; it lets current to be controlled directly, or allows other parameters such as power, reactive power, dc or ac voltage to be controlled,
- Frequency-control mode, which controls the frequency of the oscillator.

In VSC-HVdc scheme the dc bus voltage must be controlled to force the desired real power to flow in transmission line. Also the real and reactive power may be controlled simultaneously, and independently of each other. Here, an ac system fault that depresses ac voltage on phase(s) may lead to dc over voltage and over current. So every protection action must be resolved quickly (within 10-20 milliseconds). When the system is recovering from a disturbance, the controls must be fully functional, running free of limits and not suffering from extended blocking of firing pulses.

2.8 Basic protection requirements

The protection is aimed at protecting the converter substation from damages caused by external faults, or limiting the damage in case of an internal fault within the substation itself.

2.8.1 LCC-based systems

A LCC-HVdc system needs substantial filters and shunt capacitor banks. If an LCC is stopped from working (e.g. due to a short circuit), its reactive power needs would become zero, which will lead to an overvoltage at terminal bus. Also, if the system's impedance is high (low SCR), overvoltage at non-fundamental frequencies may also appear. By fast controlling of reactive power in HVdc systems, it is possible to lower the over voltages.

For an ac fault at the inverter side, usually commutation failure in converter valves is expected, which in turn may lead to temporary interruption of power transmission. For faults that occur on the dc side of the transmission system, the LCC automatically reduces the current to a small value due to VDCOL operation. However this current cannot be cleared by breaker opening, so the dc system can never be restarted without operating both of the converters in inverter mode. For recovery from dc faults rectifier is required to temporarily go into inverter mode and thus de-energize the line, referred to as 'forced retard' [5].

2.8.2 VSC-based systems

VSC-HVdc protection is very similar to LCC-HVdc protection. In external temporary faults such as voltage dips, different ac temporary over voltages, ac voltage phase shifting and ac voltage unbalances the VSC may have to stop power transmission until complete clearing of the fault. If the fault happens in the dc overhead transmission line in majority of the cases it would be a temporary one, but for the first time in a recent project to be commissioned soon in Caprivi project [96], some solution for overhead transmission line against dc fault and lightning has been proposed. In the cable transmission systems, however, it is likely that dc fault to be permanent and the converter should be shut down. In such cases as direct current will keep feeding the fault by the reverse diodes in the connected terminals, and in order to clear the fault, the ac circuit breakers at all terminals have to trip.

In case of internal faults, such as internal ac bus fault, dc bus fault or component failure, the protection equipment in VSC substation will isolate the faulty element and shuts down the transmission system.

2.9 Benchmark for HVdc system simulation studies

Benchmark systems are useful for evaluating system performance, as their nominal operation has been studied and documented. The LCC-based systems have a well known benchmark used in many studies, but a generally accepted case for VSC-based systems does not exist.

2.9.1 LCC-based systems

The First Cigré Benchmark model, referred to as "the Cigré Benchmark" in this thesis, is used to provide a test bed system to generate different operating and control aspects of conventional HVdc transmission systems. The specification of this system has been given in [22] and its schematic representation is shown in Figure 2.10.

In this model the dc transmission line connecting the receiving and sending ends, is a cable with simple T-equivalent representation, with each half impedance (Z_1) having a series 2.5Ω resistor and a 59.6 mH inductor, and a total lumped capacitance (Z_2) of $26\ \mu F$ in the middle of the line.

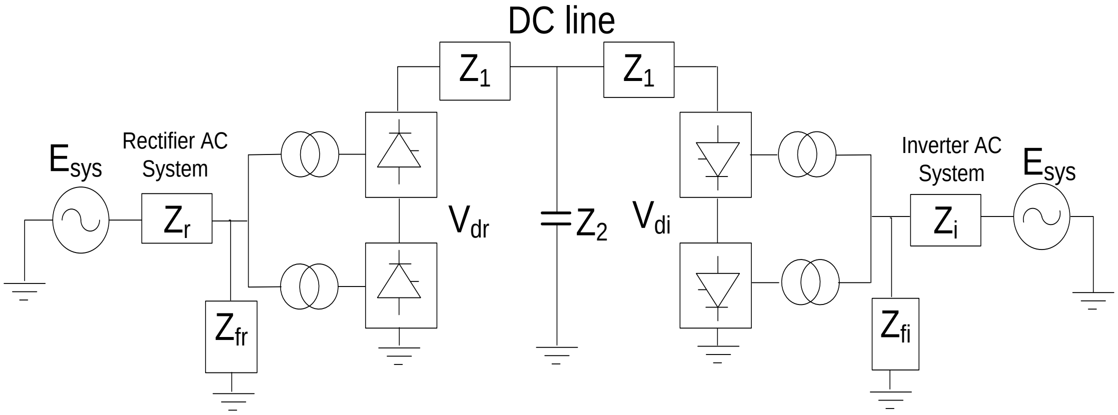

Figure 2.10 The First Cigré Benchmark model presentation

Important electrical parameters such as SCR for converters, their system-side voltages, and voltage/ power rating of inverter and rectifier transformers and their impedances are given in Table 2-1. After developing the necessary hybrid models the graphs reflecting their steady state / transient behaviors will be compared by similar outputs generated from the Cigré Benchmark results.

Table 2-1 The Cigré Benchmark specifications

Side	SCR	rms system voltage (kV, L-L)	Transformer specification		
			voltages (kV)	(MVA)	X (p.u.)
Rectifier	$2.5\angle 85°$	345	345 / 213.456	603.73	18%
Inverter	$2.5\angle 75°$	215.05	230 / 209.23	591.74	18%

2.9.2 VSC benchmark system

There is no generally accepted benchmark for VSC-based systems [85]. As will be explained later (Chapter 3), the LCC converter used in this thesis has a considerably higher rating compared to the VSC converter. As such the transient behavior of the designed hybrid converters is mainly influenced by the LCC, and not substantially by the VSC converter. Due to this fact, in the graphs reflecting transient behavior VSC-only converter is not included.

Chapter 3: Hybrid HVdc Configurations

3.1 Introduction

Converters used in HVdc transmission systems have traditionally been built based on conventional converters (LCC), and recently sometimes as Voltage-Sourced Converters (VSC). The points of strength and weakness of LCC-based and VSC-based HVdc converters were mentioned (see Chapter 2). It is highly desirable to have an HVdc system which preserves the combined advantages of an LCC and a VSC converter in one unit, without suffering from their disadvantages. These properties may be addressed in a hybrid converter structure discussed in this chapter.

The objective of this chapter is to explain the concept, design and control philosophy, along with electrical properties of the two proposed series and parallel converters, terminating into a very weak ac network. As is pointed out later in this chapter, in order to build a hybrid converter using LCC and VSC converters, an LCC-only converter (the First Cigré Benchmark) was selected as the design base. Then parts of the electrical parameters were re-designed and a combined version of LCC-VSC HVdc system controls was introduced and implemented. Finally the two controllers of the hybrid inverter and LCC-only converter on the rectifier side were coordinated and adjusted. These steps will be discussed in detail in this chapter.

3.2 Hybrid converter HVdc transmission systems

Out of different possible configurations for a hybrid converter HVdc transmission system, the series and parallel ones were selected for analysis. More complicated configurations are also possible, but it requires more complicated control methods and coordination, more semiconductor components, higher costs and more space. A hybrid converter HVdc transmission system would affect power system dynamic performance [86], [87] and can offer the following benefits:

- Generating the needed LCC reactive power by VSC converter,
- Independent controlling of the active power from its reactive power,
- Supplying a very weak ac system,
- Reducing the risk of commutation failure using fast ac voltage control,
- Reducing dramatically the size of the ac filters, if the VSC at the same time can be used as an active filter
- Possibility of using the hybrid converters in multi-terminal systems based on fast dc voltage control.

3.3 Hybrid converter arrangements

In this section the general electrical description of both SHC and PHC, along with their system requirements will be discussed.

3.3.1 Series Hybrid Converter (SHC)

A series hybrid converter consists of a series connection of one line-commutated (current-sourced) converter and one forced-commutated (voltage-sourced) converter, as shown in Figure 3.1. In this configuration the VSC converter generates the reactive power demand of the LCC converter and also supports the ac terminal voltage, while participating in active power transfer. This configuration may be considered for the following situations:

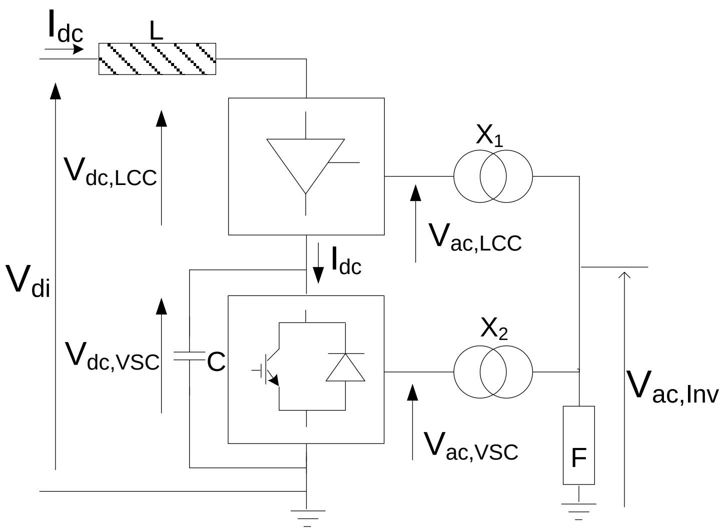

Figure 3.1 A simplified SHC-HVdc transmission system

- For building a new series hybrid converter HVdc transmission system. Providing real power to a very weak electrical system using only LCC-based converters is not possible, but a hybrid converter can provide this service. It will be shown later that the ratings of the implemented LCC and VSC converters have to be carefully selected to ensure the most economical configurations.
- For power upgrading of a weak ac system. In such a case, where increasing the dc current is not an option, the inverter voltage may be increased by using a new VSC added in series to the converter. In such a case no more reactive power support is needed, as in case of conventional converters, because the VSC has the ability of generating its own reactive power demands. It might be possible to free some of the static capacitors used to generate reactive power in the old LCC converter. If there is a need to increase the real power of the LCC-based system, it will lower the SCR of the system, which makes it more susceptible to ac voltage changes. This will prohibit using higher power LCCs under weak ac systems and

can be achieved by using a series VSC converter, which will create a SHC converter.

Another advantage of the SHC converter is that during a solid ac side fault, no real power is delivered. As a result zero power will be absorbed or delivered by the VSC terminal. On the other hand the previous dc current setting is still valid and the dc current will be flowing into series inverter circuit as before. This current will cause over-charging of VSC's capacitor before any controller takes an action. The amount of over-charging depends on the fault impedance and speed of dc current controller response. The low power demand would continue as long as the fault exists, or before any appropriate counter-action is taken. This will demand extra over-voltage protection for the capacitor.

One of the drawbacks of the SHC configuration is the complexity of "dynamic" power reversal, which needs two sets of operations. One is changing the voltage polarity across LCC rectifier and LCC inverter, without changing the current direction; here, the firing angle of these thyristors must be interchanged; secondly using mechanical switches to interchange the input-output connections for reversing the voltage polarity across the VSC. To do so, the converters need a complete shutdown. This mechanical switch will add considerably to system cost.

3.3.2 Parallel Hybrid Converter (PHC)

A parallel hybrid converter consists of a parallel connection of one line-commutated (current-sourced) converter and one forced-commutated (voltage-sourced) converter. A simplified representation for a parallel hybrid converter system (abbreviated as PHC in this research) is shown in Figure 3.2.

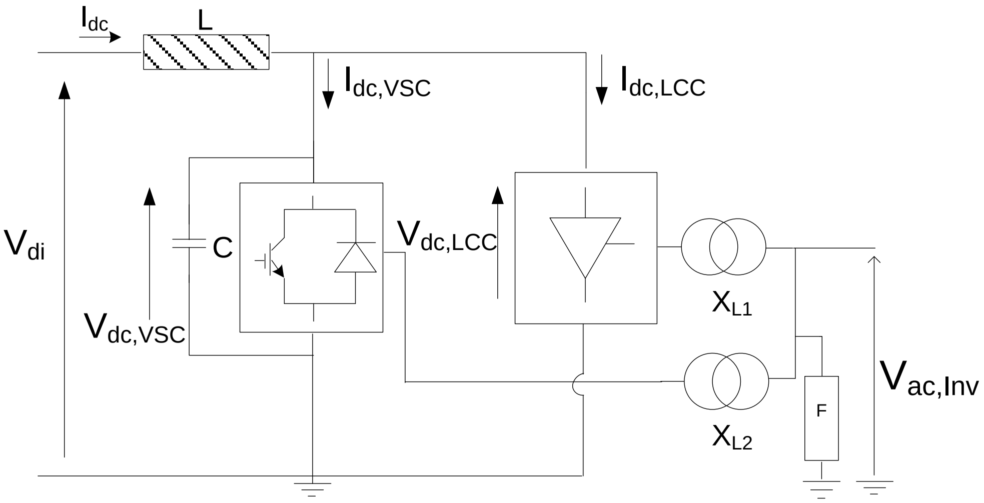

Figure 3.2 A simplified PHC-HVdc transmission system

This configuration may be considered for the following situations:

- For building a new parallel hybrid converter HVdc transmission system. Providing real power to a very weak electrical system using only LCC-based converters is not possible, but a hybrid converter can provide this service. It will be shown later that the ratings of the implemented LCC and VSC converters have to be carefully designed to ensure the most economical configurations
  - For power upgrading of a weak ac system. In such a case, where increasing the voltage levels is not an option, the inverter current may be increased by using a new parallel VSC added to the converter. In such a case no more reactive power support is needed, as in case of conventional converters, because the VSC has the ability of generating its own reactive power demands; it might even be possible to free some of the static capacitors used to generate reactive power in the old LCC converter.

At present, VSC ratings are limited to a smaller value than for LCC; because of the difficulty in series connecting forced devices such as IGBT to make a high voltage valve.

In either case the voltage rating will be limited to the highest level possible that the semi-conductor technology (IGBT or GTO) supports, which today is much less than the voltage rating of thyristors. Due to the practical voltage limitation mentioned, it would be difficult to use this topology for very high-voltage applications. In a fresh design, more options are available for selecting the appropriate voltage/current levels in the hybrid inverter but compared to SHC option, the VSC's power share in transmitting high power to weak ac systems is expected to be limited.

One of the drawbacks of the PHC converter is the complexity of "dynamic" power reversal, which needs the voltage polarity of the circuit to be reversed. To do this, the thyristor connections must remain unchanged in both the LCC rectifier and LCC inverter.

The firing angle range must be suitably modified to the appropriate operating requirements, i.e. rectifier (with alpha angle less than 90°), or inverter (with alpha angle bigger that 90°). Here, similar to SHC case, the mechanical switches will reverse the VSC inverter input-output connections. This will add considerably to system cost. Again, power reversal demands complete converter shutdown.

3.4 Main components of HVdc electrical system

One of the advantages of the hybrid converters is that they can operate into very weak systems. The following section discusses the design requirements of hybrid converters. For purpose of discussion a specific candidate system is envisaged, which is discussed below.

3.4.1 The inverter ac network equivalent

The ac network on the inverter side is represented by a RL-type equivalent circuit (Figure 3.3), connected to an ac terminal with 230 kV voltage, to deliver the rated electrical power of 1000 MW (1 p.u.), with a short-circuit ratio (SCR) equal to 1.0, which represents a very weak electrical network [4]. Such a low SCR is out of the range of any LCC-only based converter. Such a very low SCR is used to investigate the ability of hybrid converter to operate in very weak ac systems. VSC has the ability to work with very low SCR systems, but as this is a hybrid converter, the overall system performance is not dictated by just one of the converters.

The SCR is a measure of the ac network strength at fundamental frequency with respect to its transmitted dc power, defined as short circuit MVA rating, divided by system dc power:

$$SCR = \frac{SCMVA}{P_{dc}} \tag{3-1}$$

The effective-short-circuit-ratio (ESCR) is a measure of system strength when the effect of passive shunt compensating devices (i.e. filters, capacitors) is included:

$$ESCR = SCR - \frac{Q_C}{P_{dc}} \tag{3-2}$$

In (3-2) Q_C is the reactive power generation (in Mvar) and P_{dc} is dc power rating of the HVdc system.

The system impedances are predominantly inductive. Here a system damping angle of 75° is assumed for the impedance as this is typical. The system ac network equivalent is inversely proportional to the SCR. The ac network equivalent Z_{sys} may be calculated as follows, where V_p is the magnitude of the ac phase voltage:

$$\left|Z_s\right| = \frac{\left|V_p^2\right|}{P_{dc}.SCR} \tag{3-3}$$

Using the 1000 MW for P_{dc}, 230 kV (L-L) for V_p, SCR = 1 and mentioned system damping, the following system equivalent impedance is calculated; it must also satisfy equation (3-3) at fundamental frequency:

$$Z_s = 13.691 + j\,51.097\ \Omega \tag{3-4}$$

A schematic for the system with the selected RL equivalent is shown in Figure 3.3.

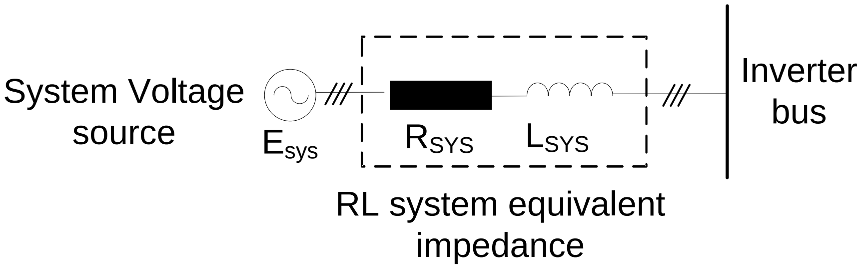

Figure 3.3 RL equivalent network

This system impedance gives an SCR equivalent of 1.0, with damping angle of 75 degrees inductive at fundamental frequency, resulting in a predominantly inductive equivalent network. In such an equivalent circuit, the electrical system behaves mainly inductive at higher order harmonics and offers less damping. Less damping results in a more difficult general parameter adjustment for the whole system and is a tougher test for system performance under different operating conditions.

3.4.2 The dc smoothing reactor

In conventional converters the smoothing inductors (reactors) are located at both ends of the dc connection, between the dc filter and bypass breakers. In the back-to-back schemes, the smoothing reactor can also be connected to the low-voltage side of dc loop [98]. The reactor must [4]:

- Limit the rate of rise of dc fault current to prevent commutation failures
- Prevent the resonances in dc circuit at low order harmonic frequencies such as multiples of 2 or 3 of the fundamental frequency (harmonics that originally start from the ac system, like negative sequence and transformer saturation)
- Reduce harmonic currents including limiting the telephone interference.

It is a complex matter to choose a feasible size for this reactor. This size is often selected in the range of 100 to 300 mH for long-distance dc links and 30 to 80 mH for back-to-back stations. Here a value of 200 mH is chosen for the smoothing reactor in both of the hybrid HVdc alternatives, which meets the above mentioned objectives.

These reactors are of two basic design types: dry-type and oil-insulated reactors in tank. The latter is an economical option for very high power levels. The reactor type should be selected based on inductance, costs, maintenance and location of spare units, and seismic requirements. Transiently, it must tolerate maximum dc voltage and short circuit current. In steady state, tolerate sum of harmonic voltages.

3.4.3 Dc harmonics and dc filter circuits

The characteristic harmonic voltages on the dc side are of frequencies $12.k$, where $k = 1,2,...n$, is the multiplier of the system fundamental frequency is (f_0). Despite the smoothing reactors in the dc lines, the harmonic currents caused by these harmonics voltages can exceed the allowed harmonic distortion level for communication interference set by standards and need to be suppressed using dc filter circuits. Based on the difference between these harmonics (for example the 12th harmonics on the two sides) the current harmonic of the order 12 may flow in the dc line. The configuration of the dc filters is very similar to the filters normally used on the ac side of the HVdc station. In cable transmission line, interference with communication circuits is minimal, so filters can be avoided.

In the benchmark system used in this thesis to demonstrate the hybrid converters, dc filters are not used because as the benchmark is developed for a cables system [68].

3.5 Hybrid system general description

The benefits offered by the hybrid topology are more applicable on the inverter side, because an LCC-only type inverter is more likely to have commutation failure and other voltage related problems when connected into a weak ac system. Hence in order to keep the simulation simple, only the inverter of the Cigré Benchmark system was replaced with the hybrid options. The original LCC of the benchmark was retained on the rectifier side. As a result, both of the series and parallel hybrid converter options consist of two six-pulse conventional LCC converters at the rectifier side. The inverter consists of series and parallel connection of 2 six-pulse LCC-only converters to make a 12-pulse configuration, and one VSC converter, to form the SHC and PHC hybrid converters, respectively Connecting points B-C forms the series hybrid inverter, while connecting points A-C and B-D forms the parallel hybrid inverter (Figure 3.4). In the SHC option, the VSC is located between the LCC and ground to reduce the voltage insulation levels (i.e., bushing insulation, etc.) of the VSC. This does increase the insulation levels required for the LCC part, but the rationale used here is that the VS's cost must be kept as low as possible, considering its greater complexity .PSCAD circuit diagrams used for both of the hybrid options are given in Figures D-1 and D-2, respectively.

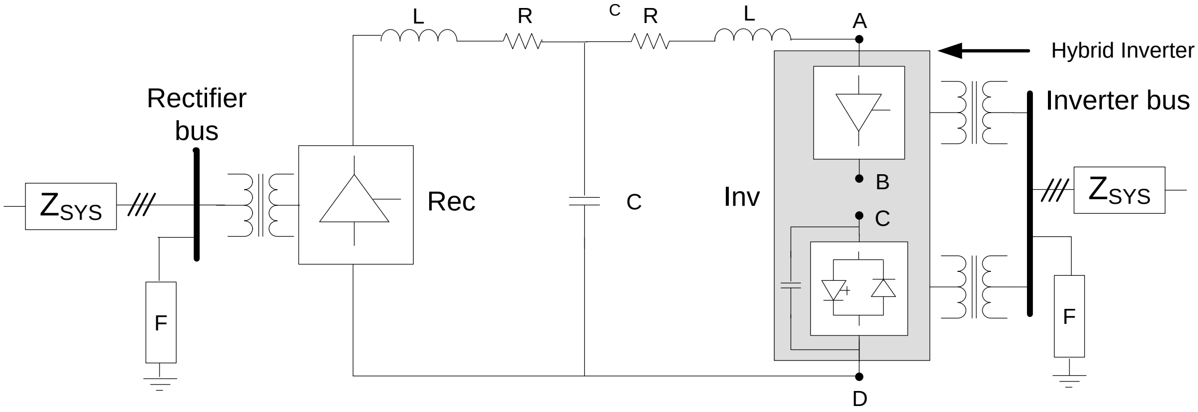

Figure 3.4 General hybrid converter based HVdc transmission system

The converters on both sides are also equipped with their corresponding transformers to provide necessary reactance for thyristors' commutation, and also to match the voltage rating at two sides. Using two different types of transformer connections, Y-Y and Y- Δ, cancels out the 3rd harmonics and its multiples from the rectifier side. The resulting characteristic harmonics (11th, 13th, 23rd, 25th, etc) are filtered out using wideband low pass filters. The VSC is connected through a Y-Y connected transformer to the inverter terminal. The converter side of transformer is grounded.

An HVdc transmission line, rated at 1000 MW, 500 kV dc with its electrical parameters as given in [22] connects the LCC-rectifier side to hybrid-inverter side. The hybrid inverter side filters will be discussed later (Section 3.9.1). The inverter side system frequency is 60 Hz. The rectifier side has the original 50 Hz frequency of the Cigré

Benchmark model. The IGBT valves of the VSC are assumed to switch at 1620 Hz (27th harmonic of 60 Hz) and thus will only contribute switching frequency harmonics.

The selection of power and voltage ratings is based on an optimization concept, discussed below.

3.6 Hybrid design philosophy

The design of the hybrid system is described in the context of the 1000 MW, 500 kV Cigré Benchmark model [22], which is to be the host system for the hybrid options. The power and voltage rating for hybrid options are thus as for the Cigré Benchmark model.

The inverter side of the Cigré Benchmark model has been completely re-designed to retrofit the VCS converter. This converter would appear in electrically series or parallel connection to the LCC converter. The rectifier converter is left unchanged. From the above discussion the total power for both of the simulated hybrid converters is 1000 MW, under 500 kV dc transmission voltage level. The question is now how allocate the proportion of this power to the LCC and VSC components.

3.6.1 Hybrid power and voltage/current allocation

The proposed method to find the suitable proportion of voltage for the SHC (and current for the PHC) option between the LCC and VSC converters at the inverter side is as follows. The key critical element chosen is optimizing (minimizing) the total system expenses. The costs involved in construction of converters for HVdc transmission has many components. It depends on price for the semiconductors used (thyristors for the LCC converter and IGBT for VSC converters), number and size of filters, land, and a number of issues specific to each project. The loss can also be included in cost analysis.

In this thesis, a detailed cost comparison was considered to be beyond the scope of the work and hence it was not conducted. The ddifficulties in conducting a cost analysis include the following:

- The price for semiconductors used for making the valves is rapidly changing overtime.
- A sufficiently large number of VSC projects simply does not exist, to suggest an established market price.
- The cost information is not available in public domain for most awarded projects.

The method employed here optimizes a suitable cost function that establishes a connection between converter voltage rating, and major system components' price. The VSC is the most expensive component, hence to achieve the desired performance with the least expense, i.e. least MVA, VSC is the actual objective used in the design. Based on the nominal power (P_{nom}) of the HVdc transmission system and the total dc voltage rating the voltage and power rating for the converters at the hybrid-side may be calculated. This very idea will be applied to both the series and parallel options here.

If P_{nom} is the total power from the hybrid converter, and P_{LCC} is the power rating of the LCC converter, then the VSC converter's power rating is given by:

$$P_{VSC} = P_{nom} - P_{LCC} \tag{3-5}$$

Also the reactive power generated by the VSC must satisfy reactive power requirement of the ac filters and the reactive power demand of the LCC converter at rated power. Assuming the reactive power demand of the LCC converter to be approximately 60% of the real power [4] and that part of this (Q_f) is satisfied by the ac filters; the required reactive power from the VSC converter becomes:

$$Q_{VSC} = 0.6 * P_{LCC} - Q_f \tag{3-6}$$

Based on the above observations, the hybrid converter's total complex power MVA rating becomes:

$$S_{VSC} = \sqrt{P_{VSC}^2 + Q_{VSC}^2} \tag{3-7}$$

or

$$S_{VSC} = \sqrt{(P_{nom} - P_{LCC})^2 + (0.6 * P_{LCC} - Q_f)^2} \tag{3-8}$$

To select the relative ratings of the converters, it was decided to minimize S_{VSC}, because the VSC is the most expensive element in the hybrid. If accurate relative costs, including other cost elements like cost of land are known, a more precise rating estimate would be possible. Considering the above, the optimum size of the VSC can be calculated by taking the derivative of VSC's complex power with respect to P_{LCC} and setting the result equal to zero:

$$\frac{\partial S_{VSC}}{\partial P_{LCC}} = 0 \Rightarrow P_{LCC(opt)} = \frac{2P_{nom} + 1.2\,Q_f}{2.72} \tag{3-9}$$

Hence

$$P_{VSC(opt)} = P_{nom} - P_{LCC(opt)} \tag{3-10}$$

Based on this result the appropriate LCC and VSC transformer ratings can be determined. Note that in this arrangement, all the reactive power of the LCC could have been provided by the VSC converter. However, for absorbing the LCC-generated harmonics, some filtering ($Q_f \neq 0$) is still required. The selection of Q_f value is discussed later (Section 3.9.1). Once P_{LCC} is determined as (3-8), the voltage ratios for the VSC and

LCC for the series hybrid option are calculated (Appendix A.2). For the SHC option, the voltage ratios are:

$$V_{dc,LCC} = \frac{P_{LCC}}{I_{dc,rated}} \quad \text{and} \quad V_{dc,VSC} = 500 - V_{dc,LCC} \qquad (3\text{-}11)$$

For the PHC option, knowing that $V_{dc,LCC}$ equals $V_{dc,VSC}$ (500 kV), similar relations for $I_{dc,LCC}$ and $I_{dc,VSC}$ can be written. Now similar calculations would result in the current ratios for the parallel hybrid option (Appendix A.3).

Note that for the design in (3-8), the filter rating Q_f must be first decided. The filter reactive power generation of around 75 Mvar was enough for steady-state system operation but it could not meet the THD (total harmonic distortion) and the individual harmonic distortion levels, as specified by the standards [68]. Q_f was selected to meet a standard THD level of 2% and individual harmonic distortions of 1%, assuming 2% tolerance in component magnitudes [88]. The filter ratings are specified in section 3.9.1.

At the same time it was of more interest to keep the reactive power generation to lowest possible level so that load rejection overvoltage at inverter terminal is easier to handle. Using an iterative method the final simulation-based optimized values of 103 Mvar for the SHC, and 110 Mvar for the PHC options were recognized suitable for Q_f. These values are much smaller than that of a conventional LCC configuration.

Based on these optimized magnitudes the apparent power rating for converter transformers were calculated (Table 3-1). In this table VSC and LCC refer to voltage-sourced converter and conventional converter, respectively.

3.7 VSC capacitor size selection

Selecting the appropriate capacitance for the VSC's dc capacitor involves a number of parameters. Here a compromise must be made between the amount of charge, charging time, the dc voltage ripple, total harmonic distortion and amount of individual harmonic contents both on dc transmission line and ac inverter terminal voltage, price, etc.

Table 3-1 Optimized power rating for the hybrid SHC and PHC options

Series Hybrid Inverter (SHC)					
P_{VSC}	Q_{VSC}	S_{VSC}	P_{LCC}	Q_{LCC}	S_{LCC}
216 MW	370 Mvar	428 MVA	784 MW	470 Mvar	914 MVA
Parallel Hybrid Inverter (PHC)					
P_{VSC}	Q_{VSC}	S_{VSC}	P_{LCC}	Q_{LCC}	S_{LCC}
220 MW	358 Mvar	420 MVA	780 MW	468 Mvar	909 MVA

There are criteria that can be used and thereby narrow down the reasonable range for capacitor size selection. One of the accepted criteria is that the permissible voltage change across the capacitor should be limited to $\pm 10\%$ of the voltage across it. Another criteria suggested in technical reports is that for the VSC applications the capacitor should be charged from zero, to its full amount, in around 5 ms, assuming that the charging is performed under a constant current source [47]. Combining these two, the equivalent capacitor stored energy corresponding to 10% voltage tolerance may be calculated.

Assume a 10% overvoltage, which is 108 kV *10%, or 10.8 kV (for the SHC). Also assume that the charging takes place under constant current injection (2 KA from the dc line) and the span of time is around 5 ms. Using the linear approximation $V = (1/C).I.t$ between voltage across a capacitor and the current going through it the capacitor size can be estimated. Using these numbers and the given approximation the capacitor size of around 1000 μF can be attained. This value has been used for all of the system studies performed here and no specific effort was made to optimize the VSC capacitor size, though an appropriate capacitance is suggested based on optimized system response to different working conditions using simulations.

3.8 Control objectives in hybrid design

The control strategy for the hybrid system is based on two control objectives:

- Regulation of the terminal voltage of the hybrid converters' ac busbar,
- Achieving the ordered power in all working conditions, within the full reactive power range required for voltage regulation. This power flows from hybrid inverter toward inverter terminal and normally would be equal to the rated (1 p.u.) in steady state conditions.

The hybrid inverter has been designed so that it when delivers one (1) p.u. of real power to the ac system the terminal operates at unity power factor. In all other conditions, keeping the terminal at one p.u. necessitates reactive power flow into, or out of the inverter terminal. The controllers for both hybrid options are a combination of the controls for the conventional LCC, and VSC converters.

3.8.1 System electrical information

The MVA-rating of the conventional converter transformers (such as those used for the Cigré Benchmark model) is larger by about 20% than the nominal dc power transmitted since the converter operates at a lagging power factor and also handles harmonic currents. In the proposed hybrid converter designs, the rating of the Y/Y and Y/Δ connected transformers is set to 457 MVA each. The transformer rating for the VSC transformer is chosen as 420 MVA. Important electrical system parameters for both the series and parallel hybrid options are given in Table C-3. Electrical transformer specifications for both the series and parallel hybrid options are given in Table C-4.

3.8.2 System dc transmission model

The dc-transmission line (link) has been assumed to be a cable transmission line and represented as a T-equivalent circuit (Figure 3.5) and is taken from the First Cigré Benchmark model for HVdc transmission systems [22]. The electrical parameters for the dc transmission line used in simulation are given in the Table 3-2.

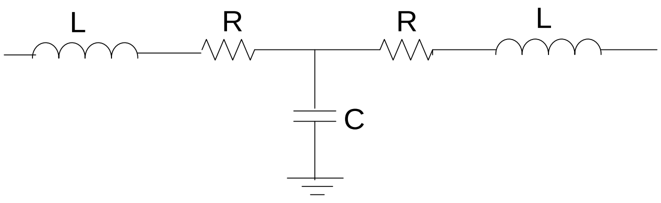

Figure 3.5 Simplified dc overhead transmission line equivalent

The hybrid options and the LCC-only converter are using the same set of electrical parameters that has been used in the Cigré Benchmark model. The inductance includes the two components of line inductance and smoothing reactor’s reactance.

Table 3-2 Electrical parameters for the dc transmission system

System	**Resistance** [Ω]	**Inductance** [mH]	**Capacitance** [μF]
SHC option	5	596.8	26
PHC option	5	596.8	26
The Cigré Benchmark	5	596.8	26

3.9 Hybrid system harmonics and filters

3.9.1 The inverter ac filters

HVdc converter stations generate characteristic and non-characteristic harmonic currents. For a 12-pulse converter, the characteristic harmonics are of the order $n = 12 * k \pm 1$, $(k = 1,2,3,...)$. These components exist even during ideal conditions (ideal smoothing of the dc current, symmetrical ac voltages, transformer impedance and firing angles). The characteristic harmonic components are the ones with the highest current level, but other components may also be important. The 3^{rd} harmonic, which is mainly caused by the negative sequence component of the ac system, needs filtering in some cases.

The most commonly used criteria for harmonic performance are related to voltage on the converter station busbar. Filter circuits for HVdc converter stations have two main duties [68]:

- Absorbing harmonic currents generated by the HVdc converter. This way the impact of the harmonics on the connected ac systems will be decreased, through providing sufficiently low impedances for the relevant harmonic components and reducing the harmonic voltages to an acceptable level. Harmonic pollution may cause premature aging and degradation of performance (even misoperation) for various components in a power system. The allowable harmonic pollution is governed by standards [68].

- Supplying reactive power for compensating the reactive demand of the LCC converter, which in case of hybrid converters this is not as important as in the LCC, because part of the LCC's reactive power can be generated by the VSC.

A commonly used criterion for all harmonic components up to 49th order is as follows:

- Individual harmonic voltage distortion of order $i\,(D_i)$ is limited to 1% of the fundamental ac busbar voltage [68].
- Total geometric sum (D_{rms}) of individual voltage distortion (D_i) is limited to 2% [68].

The telephone interference factor (TIF), which is determined from weighted individual harmonic factors, is not relevant in many cases because modern digital telephone systems are not sensitive to harmonic interferences.

The distortion level on the ac busbar depends also on the grid impedance, as well as the filter impedance. Because of that, in practice an adequate impedance model of the grid for all relevant harmonics is required in order to optimize the filter design. The detuning caused by ac network frequency deviations and component parameter deviations must also be considered when selecting the bandwidth of the filters.

Using a 12-pulse LCC converter and $Y-\Delta/\ Y-Y$ transformer connections for both hybrid converter options, the most important harmonics remained from LCC converters are typically tuned to the 11th, 13th ,23rd ,25th and 29th order.

Here singly tuned filters are assumed, as is the case in many existing systems, although new systems usually employ multiply-tuned filters [97] which are typically less expensive. However, the selection of the single tuned filters used here does not affect the essential behavior of the system.

Selecting a carrier frequency at $27 f_0$ for switching the IGBT switches in VSC converter causes the harmonics at this frequency to be suppressed because of the cancellation in the LCC transformers; however, its sidebands (25th and 29th components) need dedicated filters. Based on that, the main filters used in both of the hybrid inverter side are 11th, 13th, 23rd, 25th, 29th and 55th orders.

As explained in section 3.6.1 to satisfy the minimum THD and individual harmonic current (D_i) requirements, the minimum required filters for SHC and PHC options are 103 Mvar and 110 Mvar, respectively. Smaller size filters cannot satisfy the THD nor the individual harmonic requirements set by the IEEE standards [68]. Also low Mvar filters offer narrow bandwidth which may not be sufficient to cover normal system frequency fluctuations. On the other hand, if the Mvar rating of the filters is too high, large transient overvoltages can occur upon load rejection, or in similar transient events. The selected filters and their values target the above mentioned frequencies and satisfy the bandwidth requirement for detuning, and yet give acceptable transient response.

Table 3-3 specifies total reactive power generation capacity for the hybrid options and for the LCC-only option. Each of the singly-tuned band-pass filters used in hybrid structures consists of a simple series electrical connection of a resistor, inductor, and capacitor. The P_{total} refers to total inverter active power. In Appendix B, filter frequency response for the series and parallel hybrid systems, and the impedance plots are given.

Table 3-3 The reactive power for the hybrid, and the Cigré Benchmark options

System	Filter rating (Mvar)	$Q_f \, / \, P_{total}$	Shunt capacitors (Mvar)	Total (Mvar)	$Q_{total} \, / \, P_{total}$
SHC	103	10%	-	103	10.3%
PHC	110	11%	-	110	11%
The Cigré Benchmark	502	49.5%	125	627	62.7%

As mentioned before the detuning effect is another important parameter in selecting individual harmonic filters and their individual ratings. Ac filters must be designed so that the total harmonic distortion remains within specified limits with a small amount of detuning [89]. One possible reason for such detunings is electrical parameter changing due to aging; another reason could be the capacitor bank failure. The standards demand that based on $\pm 2\%$ change in tuned frequency of a filter, the THD should be less than 2%, with no individual harmonic exceeding 1% of fundamental component.

Simulations were carried out to assess the level of filter sensitivities due to filter detuning. The inverter-side ac source was subjected to ± 1.2 Hz frequency changes and the resulted THD and individual frequency components generated were carefully observed. At either of these levels of frequency deviations, the THD levels is around the 1% level (less than 1.5% set by the standards [68]); also neither of the individual harmonic components exceeded the 1% limits (set by the standards). The THD in each of the disturbed frequencies for both of the hybrid options is listed in Table 3-4.

Table 3-4 THD comparison in hybrid options

THD (%)	Series Hybrid Converter	Parallel Hybrid Converter
At 60 Hz (f_0)	0.9	1.1
At 61.2 Hz (102% f_0)	1.18	1.15
At 58.8 Hz (98% f_0)	1.2	1.3

The final filter orders, along with inductor, capacitor and resistor values used in simulation cases are tabulated for both of the SHC and PHC options and given in Table B-1. The total 3-phase reactive power generation by harmonic filters in the series and parallel hybrid inverters are 103 and 110 Mvar, respectively. The total 3-phase real power loss by harmonic filters in the series and parallel hybrid inverters are 0.8 and 1 MW, respectively.

In Table 3-5 the relative harmonic strengths (D_i) for the low-order, important individual frequencies, which had dedicated installed filters, have been given for both of the hybrid options. The complete table is given in Table B-2.

Table 3-5 Relative voltage harmonic strengths at important individual frequencies

Harmonic Component	D_i content for SHC (%)	D_i content for PHC (%)
11th	0.24	0.25
13th	0.15	0.18

3.10 Hybrid level converter controls

This section describes the higher level controls that generate firing angle (α) for LCC and the voltage reference signal for VSC, that is used by the conventional control strategies for conventional converters, hybrid converter control strategy, VSC control method, and the method for controlling the hybrid options (combined LCC-VSC converters).

3.10.1 The conventional LCC converter

There are two conditions required to be fulfilled for the thyristor valves to attain the conduction state (Section 2.3.1.1). The thyristor must be forward biased (positive anode-cathode voltage), and a firing signal must be present at the gate. Each valve conducts for 120 degrees during each cycle and ceases conducting when the valve current reaches zero. It must be remembered that because of series inductances in the circuit, an overlap interval will be introduced during which both the in-coming and the out-going valves are conducting. During one cycle, the normal firing sequence for upper valves commutates periodically between valves (Table 3-6).

Table 3-6 Thyristor valve conduction sequence and firing order

<table>
<tr><td>Bridge valves</td><td colspan="6"></td></tr>
<tr><td>Upper</td><td colspan="2">V4 (c-a)</td><td colspan="2">V6 (a-b)</td><td colspan="2">V2 (b-c)</td></tr>
<tr><td>Lower</td><td>V3 (b-a)</td><td colspan="2">V5 (c-b)</td><td colspan="2">V1 (a-c)</td><td>V3 (b-a)</td></tr>
<tr><td>Conduction</td><td>60°</td><td colspan="2">120°</td><td colspan="2">120°</td><td>60°</td></tr>
</table>

For each valve, a phase-locked-loop (PLL) generates a triangular signal which increases linearly from zero to unity during every cycle [90]. Having selected the appropriate gain and time constants, the PLL output tracks the phase of the fundamental frequency positive sequence component of line-to-line ac voltage at the inverter bus. The

PLL output can thus be used as an accurate reference for generating the firing pulses as discussed in [90].

These firing signals are sent to each valve when its triangular signal becomes larger than the firing signal. The mentioned ordering sequence is managed internally by a standard PSCAD/EMTDC converter model. This block issues the firing commands to valves of the LCC converters [12].

3.10.2 The VSC converter

The IGBT valves have identical positioning order and firing sequence as mentioned for the thyristor valves. The triggering pulses for switches are based on the PWM method (Section 2.5) where a triangular carrier is compared to the three phase sinusoidal reference voltages measured at ac inverter terminal voltages. The main difference between thyristor and IGBT switching operation is that the former will be switched only once in a cycle and conducts for 120 degrees while the latter may be turned on and off repeatedly in each cycle, with 27 times the system base frequency (f_0) of 60 Hz, based on the outcome of compared signal levels.

3.10.3 Traditional control strategies for conventional converters

The majority of existing HVdc-schemes operate in current control mode at the rectifier side and at extinction angle (γ) control mode at the inverter side [4]. To ensure successful firing, a minimum firing angle (α) of about 5° is required at the rectifier side, so that a sufficient positive voltage across the valve exists at the time of firing. For better control flexibility it is preferred to have a steady-state firing angle within a tolerance band around

15°, ensuring that the reactive power consumption at the inverter is kept at a minimum level without causing commutation failure.

Decreasing the extinction angle (γ) will cause an improvement in inverter power factor but, on the other hand, the probability of commutation failure increases as this angle decreases, leaving only a narrow tolerance band of $15-20^{\circ}$ for the steady-state firing angle.

It is clear that there is a trade-off between low and high extinction angles (γ) at the inverter side, which brings low reactive power consumption, and low risk of commutation failure, respectively. The voltage source in the inverter ac network is adjusted so that the extinction angle becomes 15° and 20° for the SHC and PHC inverter options, respectively. Knowing that the voltage control through adjusting the angle order has limitations, or in cases that firing angle and the extinction angle (γ) exceed their tolerance band for more than a few seconds [91], the slow tap-changer control at the converter transformers may be used to keep these angles within their desired range. In this research the tap-changer control has not been considered because its response time (around 1 second) falls beyond the transient time scale.

When the inverter operating in extinction angle (γ) control mode, the higher the line capacitance, the more difficult it would be to operate. When a disturbance causes a reduction in the ac inverter bus voltage the V_{di} (inverter dc voltage, measured on the converter side of the smoothing inductor), the negative resistance characteristic of the inverter causes the voltage across transformer leakage reactance, and the extinction angle (γ) to decrease, which increases the chance of commutation failure [92]. This reaction is more pronounced when there is no fast-acting ac voltage control device close to the inverter bus. The negative resistance is not much evident in the hybrid inverter options because of different dominant control mode chosen for the inverter side.

3.11 Hybrid converter control strategy

The nominal control strategy at the rectifier end for both of the hybrid options, based on control objectives (Section 3.8) for hybrid converters, is power control outer loop with a current control inner loop. However, a backup voltage control mode becomes necessary for the PHC option. The description of the control strategies for the VSC and LCC converters for the two options are presented below.

3.12 Decoupled vs. direct control of VSC converters

In power systems it is desirable to have independent control on real and reactive power changes. Here, the two conventional methods used to control VSC converters are discussed.

3.12.1 Decoupled method

In order to make real and reactive power changes independent the decoupled method is often used [84]. The complete general schematic for dq-based VSC control has been illustrated in Figure 3.6. All signals are referenced as direct and quadrature components. The direct (d-axis) component is in phase with the positive sequence phase of voltage and the q-axis is in quadrature with respect to d-axis.

VSC control has three parts. In the first part, the reference and measured dc voltages of the VSC capacitor ($V^*_{dc,VSC}$ and $V_{dc,VSC}$) are used to issue the i_d reference signal (i^*_d). This signal determines the real power reference command at VSC converter. The rms fundamental component of phase a terminal voltage (E_{a1}) along with its reference value (E^*_{a1}) are used to generate the i_q reference signal (i^*_q). This signal determines the reactive power reference command for VSC converter. The d and q components of VSC current ($i_{d,VSC}$, $i_{q,VSC}$) signals, flowing from VSC toward the inverter terminal are extracted using angle output of a PLL block, locked to the ac terminal voltage. Finally the d-q voltages at virtual inverter terminal (V_d ,V_q) will generate the output signals of the modulating index (m) and VSC's power reference (ϕ) signals for the IGBTs. As described before a phase locked loop (PLL) is used for synchronization with the ac network voltage. The "d" and "q" components described above are resolved by using this signal.

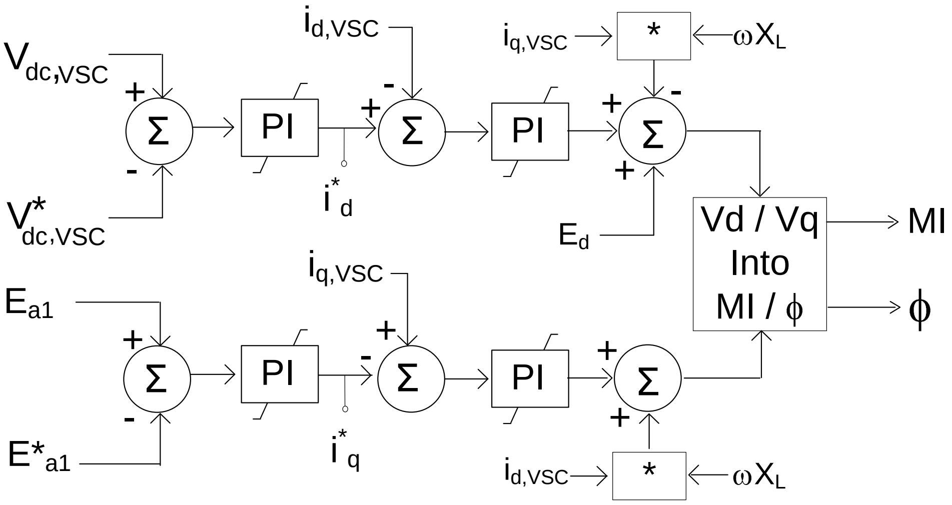

Figure 3.6 Decoupled-based VSC control

3.12.2 Direct method

Direct control method is another strategy that can be used for controlling VSC-based HVdc systems (Figure 3.7). In the simulation of the designed series and parallel hybrid inverters it was observed that because of the delays introduced in generating voltage signal components (direct V_d and quadrature axis V_q signals) the fault recovery was not fast enough, and in cases was accompanied with short term commutation failures. The main reason found was using two PI controllers for generating the V_d and V_q signals, which are the basis for issuing the modulating index (m) and phase angle (φ) signals. One advantage of the direct method is that it does not require the ac side impedance to be a parameter of the control structure – a quantity which must be known accurately for the decoupled controller to perform properly, the direct control method is used in both of the hybrid options. Also in the decoupled method, the terminal bus is assumed to be an infinite bus, while in the very weak ac system investigated here this is not a valid assumption. Another advantage of the direct control method is that the total number of PI controllers utilized is less than the number used in decoupled method, which causes generally less delay and faster controller response. This method is described in more detail below.

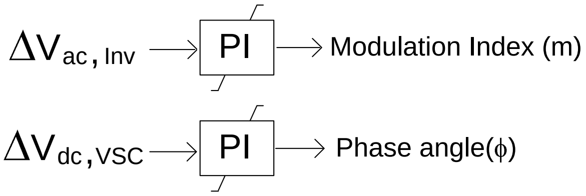

Figure 3.7 Direct method for VSC control

The disadvantage of the direct method is that the real and reactive control loops are not independent. A change in real power causes a transient in reactive power and vice-versa. However with properly tuning of the control system, such transients can be quickly brought to decay and so they are not a major concern.

3.13 Implemented VSC control for hybrid options

The VSC converter is used to regulate the ac voltage of the hybrid converter and also to regulate its dc voltage to the desired limit. The ac voltage is kept constant by changing the generated reactive power and the dc voltage by regulating the real power. The VSC is ordered to provide a voltage proportional in magnitude to the modulation index (m) and at a phase angle (φ) with respect to the fundamental positive sequence of ac voltage. Here a simple direct control [91] strategy is used for the both VSC converter options.

A phase locked loop (PLL) is used for synchronization with the ac network voltage and generates the synchronizing angle signal, as described in section 3.10.1. A pulse-width modulation method (PWM) [65] is employed to generate the necessary ac voltage with a fundamental frequency component of magnitude proportional to modulation index (m) and phase angle (φ). The PWM controller generates the firing pulses for the VSC's semiconductor switches. The command signal (m) for reactive power generation is derived directly from voltage mismatch at inverter terminal (ΔV_{inv}) for both series and parallel hybrid cases. The proposed direct controller is shown later to provide good transient performance.

3.13.1 VSC control in SHC option

The real power in the VSC is most sensitive to changes in phase angle (φ) whereas the reactive power (hence ac voltage) is sensitive to changes in modulation index (m). These two factors are used to develop the VSC control for SHC option, shown in Figure 3.8, where the ac voltage error is used to generate the modulation index, m (Figure 2.8).

Note that adjusting the dc capacitor voltage requires the input or output of real power, and this adjustment is achieved through the control of phase angle, as described above. In this figure $V_{ac,\ inv}$, $V_{dc,VSC}$ and $I_{dc,VSC}$ refer to inverter ac voltage, VSC dc voltage, and current, respectively. The “starred” values refer to their corresponding reference values. For SHC option these reference values are 230 kV, 108 kV, and 2 kA, and for PHC option these are 230 kV, 500 kV and 0.44 kA, respectively (Table 3-2).

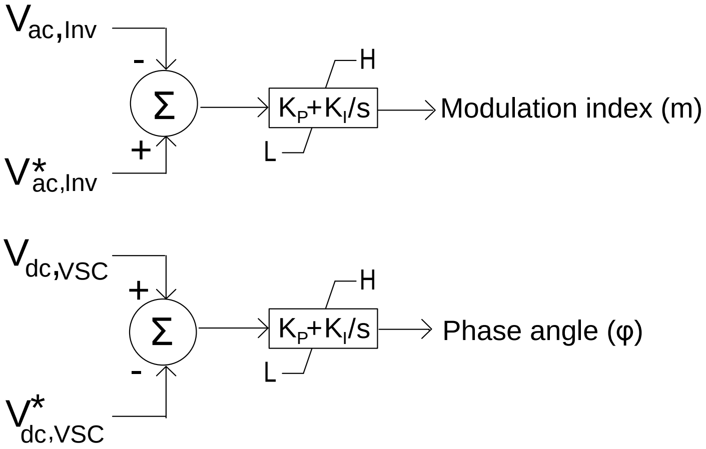

Figure 3.8 VSC converter controls for the SHC option

3.13.2 VSC control in PHC option

As in the series converter case, the modulation index signal (*m*) which commands the IGBTs is generated based on the error in the ac inverter terminal voltage of the PHC converter. In normal working conditions, with the VSC’s dc voltage being on the rated (reference) value, the VSC’s dc current mismatch will generate an error signal which is in proportion to the phase angle (φ) (Figure 3.9(a)). Using smooth transition method (Section 4.7), the lower PI controllers can be substituted with only one (Figure 3.9(b)).

The current reference for VSC is a percentage of the inverter current order (0.22) and is already specified in section 3.6.

The normal mode of operation is current-mode. The controller has been designed to select the minimum value between the dc current, and dc voltage errors of the VSC. This loop enables the PHC to have better recovery during big transients or inverter-side faults. During such occasions, normally the voltage mode is selected. A margin of 10% in voltage error has been used, before the minimum select can be activated. The output of this controller is adjusted to generate higher gains for smaller inputs.

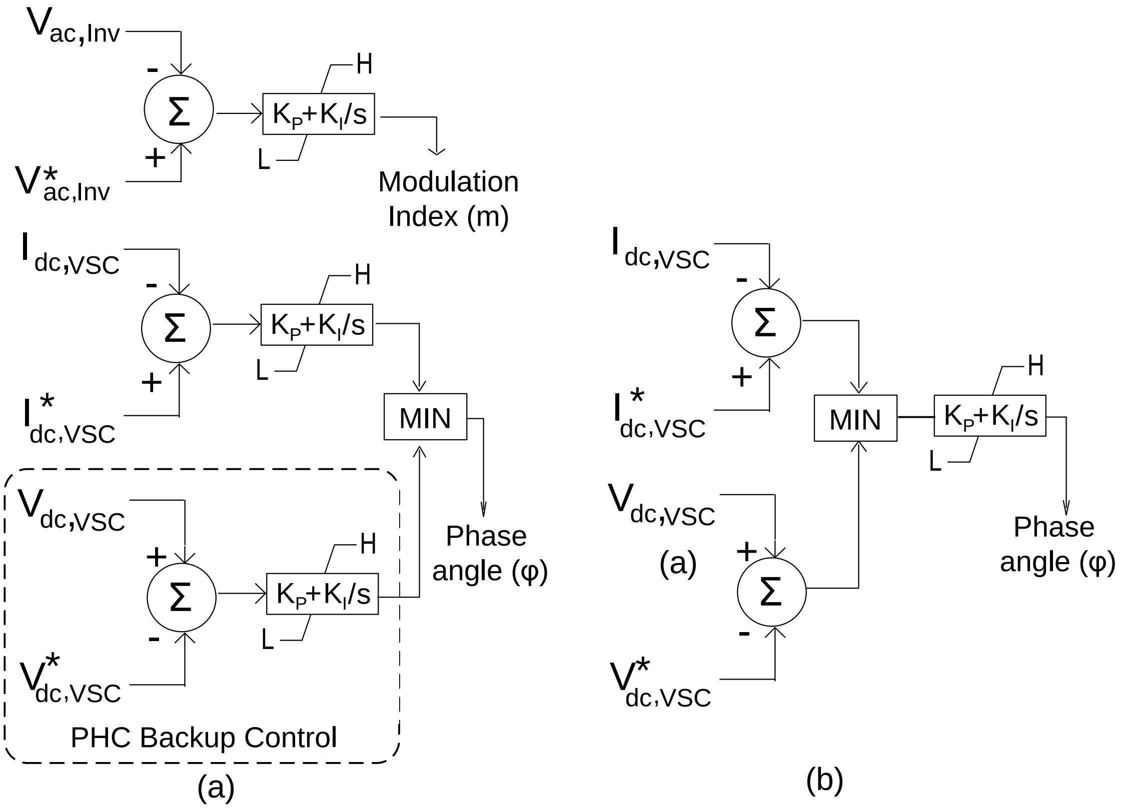

Figure 3.9 VSC converter controls for the PHC option

3.14 Circuit control strategy for the SHC converter

This section describes how the LCC and VSC parts of the SHC work together to achieve a series operation. The hybrid inverter has two separate control sub-systems. The details of VSC controller for the SHC were described in section 3.13. The details of the

LCC will be described later in section 3.14.1. The schematic control for the complete SHC hybrid inverter/rectifier system is given in Appendix C-4.

Under normal conditions the dc voltage across LCC inverter is equal to its designed dc voltage. The VSC converter keeps its dc voltage at its reference value. Hence rated powers are generated in each of these two converters. Changing the power order at the inverter terminal will cause a new LCC current order to be issued. The rectifier LCC adjusts its output current to the new order. At the same time, both the LCC and VSC converters try to adjust their output voltages. In steady state, the controllers will cause the ordered power to be generated at the inverter side.

The series hybrid inverter scheme has been designed such that the VSC maintains the inverter terminal voltage at one p.u., hence causing the inverter terminal to work in unity power factor. Based on this power factor the voltage-control mode would be operational during normal working conditions, which is a direct indication that ac voltage controller is able to perform the requested control task appropriately.

When dealing with a very weak system, the extinction angle-control mode was observed to be too oscillatory and difficult to control. As a result it was decided not to use the γ–control as the dominant control mode for the LCC inverter. In SHC option both the γ– and current-control modes are used as the backup modes.

In the modelled SHC option, only inverter operation of the hybrid converter was considered. The rectifier was implemented as an LCC-only converter in the current-control mode. From the inverter’s ac terminal view, VSC delivers the complete reactive power requested by the LCC inverter, which in fact may also be supplemented by extra reactive power request from the ac system, depending on available rating [9]. Looking from the dc side of the hybrid inverter, VSC plays a role in both active and reactive power generation and voltage support. Due to VSC's role in real power generation, the LCC inverter can be designed to have lower rating (Section 3.6).

3.14.1 Control of the LCC inverter for the SHC option

In the SHC option the conventional (LCC) part of inverter normally operates in voltage control mode, reverting to current-control, or extinction angle (γ) control modes at the boundaries. One boundary is when the dc current falls more than 10% (current margin) below its set value.

Current control is implemented in rectifier side. In case the rectifier is unable to control direct current then inverter must take over current control. The other boundary is when the voltage control mode causes the extinction angle (γ) to fall below $\gamma_{\min}$, thereby endangering the inverter operation. In such occasions the inverter would be forced to operate in γ–mode to avoid commutation failure.

Figure 3.10 depicts the LCC converter block diagram for the SHC option. In this figure $V_{dc,LCC}$ and $V^*_{dc,LCC}$ refer to the measured, and the reference dc voltage across the LCC converter at the inverter side, respectively.

The rectifier current order is extracted from the terminal power error signal and LCC inverter dc voltage. $I^*_{dc,Inv}$ and $I_{dc,Inv}$ refer to the reference, and measured dc current at the LCC inverter, respectively. $I_{dc,Inv}$ is the same current that flows into the VSC converter. γ^* and γ refer to the reference, and measured extinction angles, respectively.

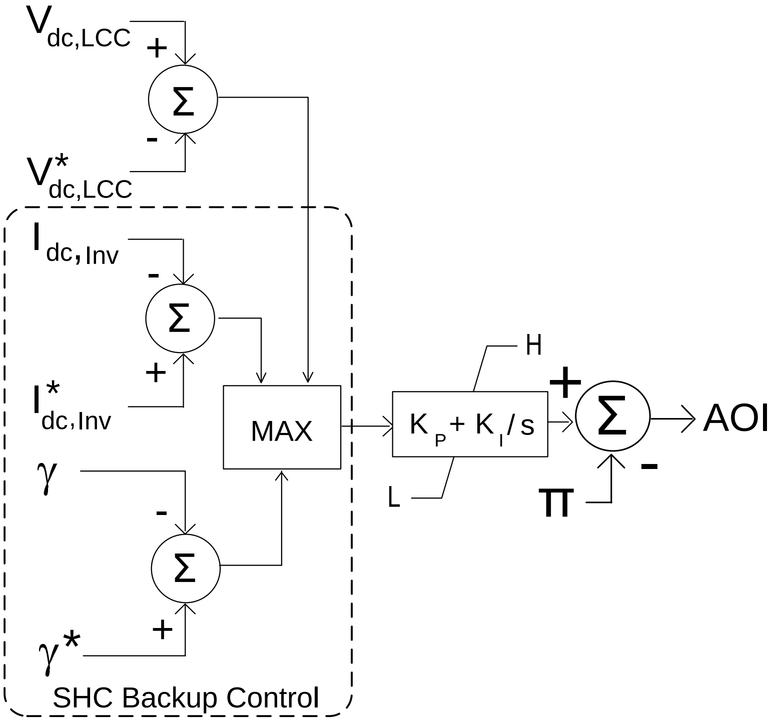

Figure 3.10 LCC inverter controls for the SHC option

3.14.2 Rectifier control for SHC design

In simulation, the rectifier controller for the SHC inverter option is modelled as in Figure 3.11. The rectifier is an LCC which operates in current control mode. The rectifier current order signal is calculated from power order signal and LCC dc voltage signal. A Voltage Dependent Current Order Limit (VDCOL) unit is implemented that reduces the current order to a low rate (30%) when needed (Figure 3.11). The appropriate parameters for VDCOL have been found based on optimization and given in Table C-2. The VDCOL output is filtered to give better system transient performance. It is discussed later, in 4.6.3.1. Based on this output, rectifier reference current signal is generated. The rectifier α - order signal is generated and sent through communication channels to the rectifier.

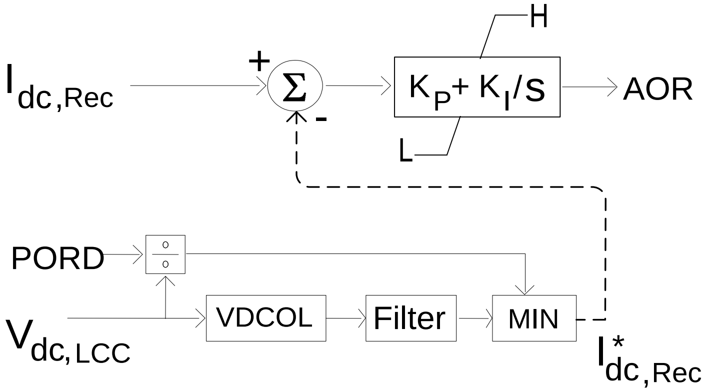

Figure 3.11 Rectifier LCC controls for SHC option

3.15 Circuit control strategy for PHC converter

This section describes how the LCC and VSC parts of the PHC function together to achieve a parallel operation. The hybrid inverter has two separate control sub-systems. The details of VSC controller for the PHC were described in section 3.13.2. The details of the LCC will be described later in section 3.15.1. The schematic control for the complete PHC hybrid inverter/rectifier system is given in Appendix C-6.

The parallel hybrid inverter scheme has been designed such that to maintain the inverter terminal current at the ordered level. At rated current, the inverter terminal works in unity power factor. Based on this power factor the current-control mode in inverter side would be operational during normal working conditions, demonstrating that current controller is able to perform the requested control task appropriately. The voltage-control is the normal mode of operation for the LCC rectifier.

PHC option, similar to the SHC option discussed before (Section 3.14) uses the extinction angle-control mode as the backup mode. During the big transients or fault recoveries, the rectifier switches to current control mode. The LCC inverter will switch to γ-control mode, and VSC switches to voltage control mode.

In the PHC modelled option, only inverter operation of the hybrid converter was considered. The rectifier was implemented as an LCC-only converter in the voltage-control mode. Similar to the SHC option discussed before, VSC plays a role in both active and reactive power generation and voltage support. Due to VSC's role in real power generation, the LCC inverter can be designed to have lower rating (Section 3.6).

3.15.1 Control of the LCC inverter for the PHC option

The LCC converter in PHC option works in current control mode, having the extinction angle (γ) as it's backup, as specified in section 3.15. The LCC converter block diagram for this option is shown in Figure 3.12.

The inverter dc current is the sum of the LCC inverter and VSC converter currents, with the ratio determined by the optimization scheme for the PHC (Section 3.6.1). When the dc voltage of the VSC converter has its reference value and both LCC inverter and VSC pass their ordered currents, the ordered power is generated.

In this scheme, the real power error in inverter terminal is used to generate a current order signal. The minimum of this signal and VDCOL output, multiplied by LCC current share (0.78, see section 3.6) generates the LCC current order ($CORD_{LCC}$). The maximum of the current and extinction angle (gamma) errors will finally generate the inverter alpha order (AOI). The LCC normally operates in current-control mode, with γ -control mode as backup control.

3.15.1 Rectifier control in PHC design

The rectifier LCC for the PHC option is shown in Figure 3.13. In normal working conditions the LCC operates in voltage control mode.

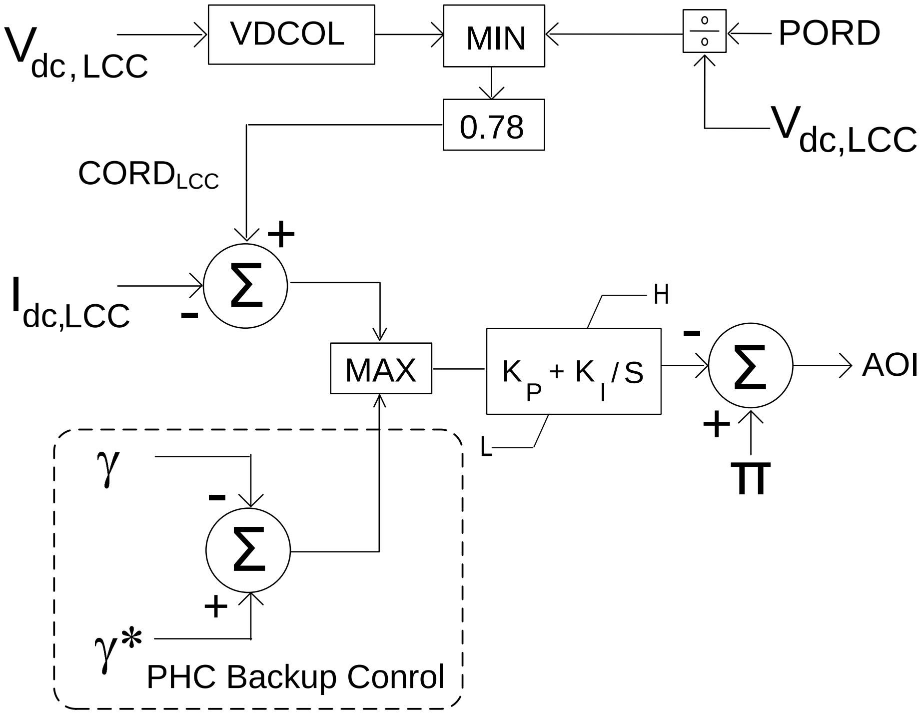

Figure 3.12 LCC inverter controls for the PHC option

During transients and fault recovery, the PHC control switches to current-control. Here, the reference LCC current is generated using the ratio of power order and LCC dc voltage. The principle of issuing this signal is the same as that used for the SHC option (Figure 3.11). The VDCOL generates a dc current signal, in proportion to the rectifier dc voltage. Its output signal is filtered to give better system transient performance. It is discussed later, in section 4.6.3.1. The appropriate parameters for VDCOL have been found based on optimization and given in Table C-2. Based on the algebraic sum of dc current error and current margin, the rectifier angle order (AOR) is issued.

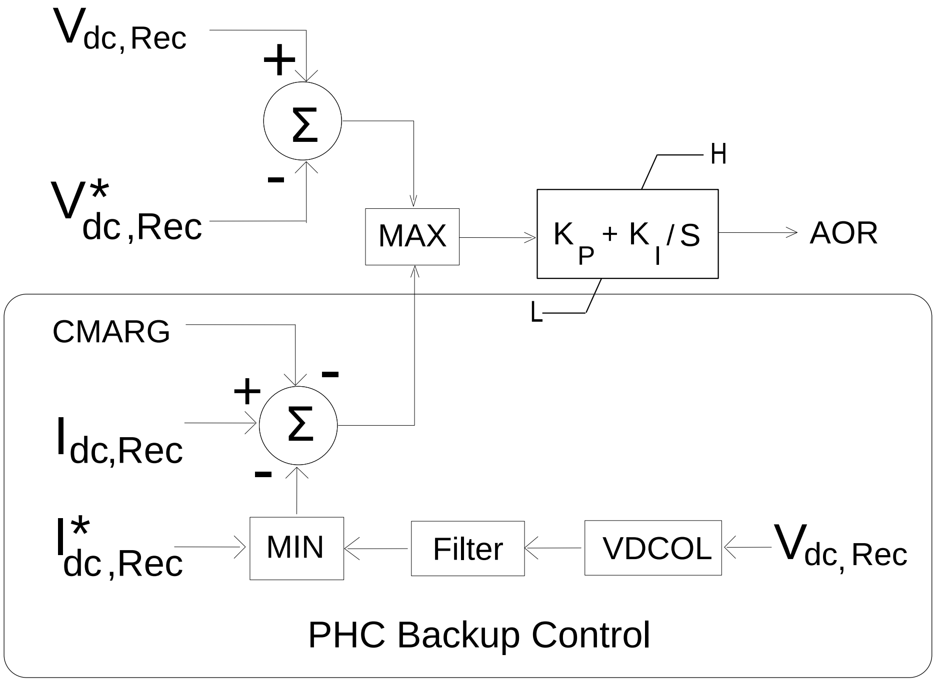

Figure 3.13 LCC controls for rectifier in PHC option

Chapter 4: Hybrid Converter Transmission System Performance

4.1 Introduction

A well-designed HVdc system should react rapidly to set-point changes, while demonstrating reasonable fast recovery from system faults. The objective of this chapter is to investigate the feasibility and suitability of different hybrid inverter topologies in an HVdc transmission system scheme, terminating into a very weak ac network. As will be pointed out in this chapter, the traditional control method of LCC systems needs some modifications to appropriately host a VSC converter. These modifications for both the series (SHC) and parallel (PHC) hybrid inverters will be first discussed in this chapter. The hybrid system behavior under these control methods will then be evaluated and compared to the LCC-only inverter scheme.

In order to investigate the performance of the two proposed SHC- and PHC-based hybrid HVdc transmission systems described in the previous chapter PSCAD/EMTDC simulation software tool will be used. System behavior will be studied under steady state, by subjecting the HVdc converters to various operating point changes, transient behavior (small and large signal changes) and system faults. The results of performance comparison between the hybrid options and the Cigré Benchmark model will be covered in this chapter.

The absence of a reported HVdc system that is capable of operating under very low SCRs makes the evaluation and performance comparison of the proposed hybrid converter HVdc systems difficult. As a trusted benchmark in HVdc systems, the First

Cigré Benchmark model for HVdc control studies (the Cigré Benchmark in this text) was selected as a test bed (Section 2.9).

Because the inverter side of the hybrid options are designed to operate under SCR = 1 and the Cigré Benchmark model for SCR = 2.5, comparing their performances cannot be accomplished based on equal system parameters and conditions. As a conventional LCC-based converter cannot operate under SCR = 1, in this research it is assumed that the original SCR of Cigré Benchmark model inverter-side is modified using reactive power generators such as fixed capacitors or synchronous condenses. The modification causes the effective short circuit (ESCR) of the Cigré Benchmark inverter system to be comparable with the hybrid converters under investigation. The behavior of the proposed SHC- and PHC-based HVdc systems was investigated by subjecting the HVdc converters to various operating point changes and system faults. Other modifications made to the Cigré Benchmark case are discussed below.

4.1.1 Modifications in inverter configuration

The principal modification was made to the configuration of the inverter side of the Cigré Benchmark model. For the SHC option, the conventional LCC inverter was replaced with a series connection of a 12-pulse conventional LCC converter and a 2-level VSC converter. For the PHC case the 2-level VSC converter was added as a shunt to the 12-pulse LCC converter. Control strategy was modified as needed. The controller parameters were optimized for an overall good performance [93], not for any particular single disturbance event (Chapter 3).

4.1.2 Modifications in inverter electrical specifications

The Short Circuit Ratio (SCR) at the ac inverter terminal was lowered considerably, to investigate the hybrid's additional capability of operating at very low SCRs. Both of the designed hybrid converters operate into a very weak ac system (SCR = 1). A conventional LCC converter would typically not be able to operate when connected to such a weak system. If we use the same amount of total reactive power generated in a conventional LCC (such as Cigré Benchmark model) with SCR =1, the effective short circuit ratio (ESCR) is as low as 0.23. This number is based on the real power generation of LCC-inverter in hybrid option. Hence, for the comparison, the model for the LCC-only option includes an ac network with SCR = 2.5 (ESCR = 1.9, after accounting for ac filters and fixed capacitors on the busbar). This larger SCR could be considered to arise from additional compensation using synchronous condensers as would be necessary to enable the use of a conventional converter.

The power rating was kept the same, but at the inverter side the original LCC's power capacity was reduced to provide some room to the newly added VSC inverter. The relative ratings were selected as discussed in section 3.6.

4.1.3 Modifications in rectifier side

The rectifier side for both hybrid options is assumed to be a conventional LCC converter identical to the Cigré Benchmark model. For the PHC option, a back-up current controller was added to the control system. The controller parameters were optimized for an overall good performance [93], not for any particular single disturbance event (Chapter 3).

4.2 Method / tools for system study

To fully analyze the proposed hybrid HVdc systems an exact mathematical model of both the LCC and VSC converters is needed. Then these models must be integrated into a single mathematical model describing the integrated system. This model enables the user to perform a small signal analysis, which will only be valid for small changes around system’s operating point and will indicate the validity of selected control parameters around this point. The complexity and extensiveness of the composite integrated system (series, or parallel hybrid converter) prevents the integration of separate mathematical models for each of the two converter types into a single model. Frequency conversion through ac-dc converters, discontinuous and non-linear nature of signal transfer through converters, complexity of interaction equations between ac-dc variables and complexity of phase locked loop (PLL) modeling will add to the complexities.

On the other hand, disruption of the normal switching sequence after a fault incident especially during commutation failure periods and shortly after it, will lead to considerable waveform distortion of the commutating voltage wave shapes, making the problem not suitable for small signal analysis.

An appropriate tool that can be used as an alternative in such cases is to perform a complete simulation-based study. Expected benefits of digital time-domain simulations are as follows:

- Ability to reproduce system performance with highest realistic degree of complexity that is desired.

- Investigating system fault modes and predicting the important parameters such as over-voltage and over-current stress on energy storage elements and switching elements at system, and at component-level.
- Achieving realistic estimate on recovery time for an HVdc system, following a disturbance
- Having a “visual image” of system behavior under different working conditions
- Providing the basis for protection requirements in a real HVdc system, if system parameters are known

However time domain solution has the following disadvantages:

- Methods for stability analyses such as eigenvalue approach which provide a “big picture” understanding are not possible
- It is time consuming to conduct extensive parametric studies

Based on the above explanations the mathematical method is not an option. Here, the numerical simulation on an electromagnetic transients solver was chosen to assess the behavior of the system and a trusted power system simulation tool, PSCAD/EMTDC, was selected and used to conduct all aspects of model implementation, carry out extensive simulation studies and assessing the overall HVdc system behavior. PSCAD / EMTDC has proved instrumental in implementing the different aspects of power system studies in general. It provides a powerful resource for assessing the proposed hybrid HVdc systems in the power network.

In this research an attempt was made for not to resort to complicated control strategies and the conventional closed-loop structure control has been used instead, trying to keep the control system as simple as possible.

4.3 Hybrid system development steps

A hybrid converter model was developed using the Cigré Benchmark model as the starting point (Section 3.6). Based on the power rating and voltages (ac and dc) of this model the two SHC and PHC hybrid models were developed. To select the appropriate power, voltage and current ratings, an optimization process was employed (Section 3.6.1).

A realistic reactive power demand for the LCC inverter and for the rating of the harmonic filters is assumed. Based on these assumptions, the specifications for hybrid inverter converters are derived. To do so, the mentioned optimization procedure was used. As the last stage, the transformer ratings for VSC and LCC converter are calculated (Appendix D.3). When simulating the designed systems, if total and/or individual harmonic content of the inverter terminal ac voltage does not meet the standard levels, it can be concluded that the total, and/or possibly some of the individual reactive power rating of harmonic filters must be revised. If the total filter reactive power generation is changed, the VSC / LCC inverter power ratings must be re-allocated. The whole design process must be repeated until the appropriate voltage and current rating, and acceptable harmonic levels are achieved. At this stage, the system operating point can be derived (Appendix A).

As mentioned before, simple PI controllers have been employed in both of the hybrid options. Because of the significant weakness of the selected ac inverter side of the designed hybrid options, a customized sequence for start-up had to be implemented.

4.4 Parameter tuning

The recovery performance for any type of fault (close-in, or remote) depends on a number of factors, such as ac system strength, dc system characteristics and controller settings. In order for the HVdc schemes to demonstrate good performance for all types of dynamic changes (faults or disturbances) the controllers need to be carefully tuned.

Fast recovery within 150 ms after the fault clearance is desirable for most normal HVdc systems. SHC option can satisfy this requirement through fine tuning of control parameters, discussed in the following section.

In case of the PHC option, achieving 150 ms recovery time proved to be impractical, as discussed in section 4.8.5.1. To avoid a chain of sequences leading to commutation failure in LCC-converter, and possible successive commutation failures in PHC LCC converter, the power recovery speed needs to be reduced. Through multiple simulation runs it was found out that around 450-500 ms recovery speed is the fastest achievable for this option.

In the simulations the control system parameters were selected based on a trade-off between the terminal power recovery speed and chances of successive commutation failure, using an iterative method. A number of control parameters need to be adjusted to achieve this goal. In the following section the method used to achieve this objective is explained.

4.4.1 Optimization tool and parameter adjustment method

To improve system performance, especially during fault recovery period, some parameter adjustments are necessary. These adjustments, in general, result in a safe and more rapid system recovery and to accomplish it, the parameters must be optimized. The extreme weakness of the selected SHC and PHC options in inverter side demands many parameters and control variables to be exploited in optimization process.

In SHC and PHC options, the PI controllers' gain and time constants for LCC-inverter, LCC-rectifier, VSC-converter, and power controller add up to 14 variables. Also non-linear parameters of VDCOL and high/low limits for PI controllers must be set. It was found practically difficult to define a reasonable objective function that considers various requirements for the hybrid options and can handle the large number of parameters that need to be adjusted.

Theoretically it is possible to define a global objective function through a linear combination of a number of local objective functions. However, assigning a physically reasonable weight to each of the different objective functions will drastically affect the results of the final objective function, and can be very subjective. Based on these facts, it was decided that the full utilization of optimization not to be used. In this research, the parameter selection is not fully based on optimization. The implemented procedure in this research has two main steps:

- Using the embedded optimization toolbox in the simulation environment (PSCAD) to first calibrate controller parameters separately.
- Fine tuning the parameters based on an iterative method to achieve better tuned parameters.

Through these investigations, it became apparent that VDCOL by itself has great influence on hybrid-based system behavior. Adding a filter with variable delay in the output of VDCOL to adjust its response speed (discussed in section 4.6.3.1) was also found to be crucial in general, to protect LCC-inverter from commutation failure. It was found that LCC rectifier’s gain and time constant also play an important role in achieving proper system behavior. Based on these findings, parameters for the VDCOL and rectifier were optimized first. Using these settings as a base, all of the other parameters were adjusted based on an iterative method. In the following two sections, the important actions taken are highlighted.

4.4.1.1 Considerations for the SHC option

Applying the following modifications/procedures made it possible to put the very weak SHC converter into operation:

- Appropriate VDCOL parameters were distinguished and utilized (Table C-2)
- The suitable response time for VDCOL’s filter was attained (Section 4.6.3.1)
- Decreasing the sensitivity of the gamma controller whenever the gamma error has an error band of smaller than 5°; this is done to lower the chance of this control mode to be selected (Section 4.6.3.2).
- The “maximum selection” logic was used to select between different control modes in the LCC-inverter; this method also inhibits controllers' saturation while deselected (Section 4.7).

The complete set of controller parameters used for the SHC option is given in Table C-5.

4.4.1.2 Considerations for the PHC option

Applying the following modifications/procedures made it possible to put the very weak PHC converter into operation:

- Appropriate VDCOL parameters were distinguished and utilized (Table C-2)

- The suitable response time for VDCOL’s filter was attained (Section 4.6.3.1)
- The “maximum selection” logic was used to select between different control modes in the LCC-inverter; this method also inhibits controllers' saturation while deselected (Section 4.7)
- Decreasing the high-limit for gamma PI controller on sensing low rms inverter voltage to decreases the chance of gamma control mode selection in competition with current control mode

The complete set of controller parameters used for the SHC option is given in Table C-5.

4.5 System start-up procedure

The detailed sequences for starting and stopping of HVdc-schemes vary depending on the load types, which are tailored to individual applications. Here the implemented procedure for both hybrid options is detailed.

4.5.1 SHC system start-up procedure

For the series hybrid inverter, both of the rectifier and inverter converters are blocked first. A delay of 0.2 seconds, gives enough time for ac busbar voltage on either side terminals) and for PLL to initialize. Then rectifier (LCC rectifier) and inverter (LCC inverter, and VSC inverter) are de-blocked simultaneously at 0.2 seconds after simulation start time,. Simulation showed that a single step to maximum power had excessive oscillatory or unstable response. Hence a 50% step is applied followed by 0.1 second ramping of power order to rated value, which provided a smoother reference.

Additionally the rectifier applies a ramped response to the current order because of VDCOL operation, as mentioned earlier (Sections 3.14.2). The VDCOL asks for the dc current reference when the voltage is low, and this ceiling is raised as the voltage builds up.

4.5.2 PHC system start-up procedure

For the PHC option, both the rectifier and inverter converters are blocked first. A delay of 0.2 seconds, gives enough time for ac bus voltage (on either side terminals) to initialize and settle. The LCC rectifier is de-blocked at 0.2 second after simulation start time. Now the LCC rectifier's phase-locked-loop can lock itself to the ac network terminal voltage, and the dc voltage starts to build up. The inverter is still blocked, which ensures that the rectifier dc voltage has gained enough positive value when the inverter de-blocks. Then VSC converter is de-blocked at 0.3 seconds. The VSC's dc capacitor is assumed to be pre-charged to the rated voltage from the inverter ac system. Finally the LCC inverter is de-blocked at 0.4 seconds. Now the power order is ramped-up slowly (in 1 second). The system will completely settles down in around 1 second. The rectifier also applies a ramped response to the current order because of VDCOL operation (Section **Error! Reference source not found.**). The characteristic for LCC inverter VDCOL used in PHC option has different settings from that of the SHC option (Table C-2).

4.6 Control considerations in hybrid inverters

4.6.1 SHC control considerations

The overall control system for the SHC LCC part was discussed before (Section 3.14.1). There are 3 control loops of voltage-control, current-control and gamma-control (Figure 3.10). The selection between these control modes is through selection of the largest error and is discussed further in section 4.7. The current-control and gamma-control modes are a little different from those in a conventional LCC. These modifications and the reasons for their adoption are discussed below.

4.6.2 PHC control considerations

The overall control system for the PHC-LCC part was discussed before (Section 3.15.1). There are two control loops of current-control and gamma-control (Figure 3.12). The selection between these is through selection of the largest error and is discussed further in section 4.7. The current-control mode in both of the hybrid options and gamma-control mode for SHC option are a little different from those in a conventional LCC. These modifications and the reasons for their adoption are discussed below.

4.6.3 Modifications in LCC-inverter control for the hybrid options

4.6.3.1 Current controller adjustment for both hybrid options

The current control loop has a VDCOL, which for SHC and PHC options is shown in Table C-2. It replaces the current order with a low value for low dc voltages. In order to lower the risk of commutation failure during fault recoveries, or transients, the system power recovery must be slowed down, which demands customized parameters for the VDCOL characteristics, and filtering. The implemented mechanism to achieve this goal is shown in Figure 4.1.

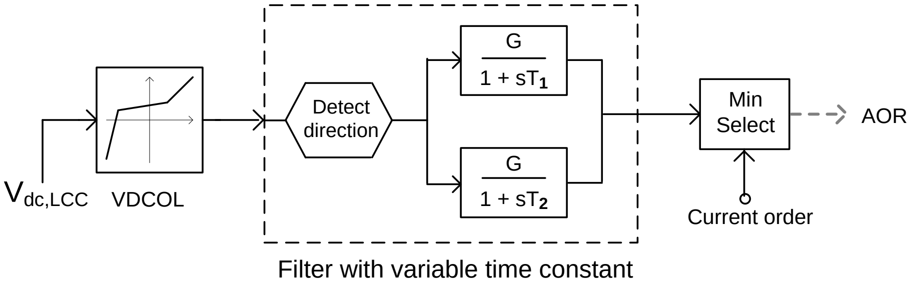

Figure 4.1 Block diagram for modified VDCOL

If the current order (output) of VDCOL is increasing, then the filter has a larger time constant, thereby slows down the current order signal going to current controller. If the current order of VDCOL is decreasing, the change is implemented more quickly (smaller time constant) because reduced current is not likely to cause commutation failure.

4.6.3.2 Adjusting the gamma control mode sensitivity for the SHC option

The inverter current order is issued based on maximum selection of voltage, current and gamma (extinction angle) error signals. The preferred control mode for the inverter side in SHC design is voltage-mode. For small deviations from the operating point it is preferred that gamma control mode does not take over the control instantaneously. Hence the gain of the gamma-controller is reduced for small gamma errors, in the $\pm 5°$ band, thereby slowing down the gamma-controller. This characteristic is implemented using a non-linear gain block with variable gains for large and small inputs (Figure 4.2). The discussed adjustment is not used for the PHC option.

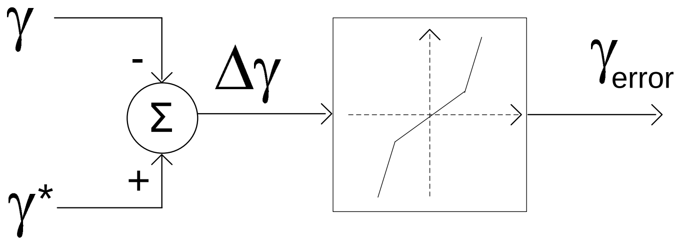

Figure 4.2 Adjusting the sensitivity of γ-controller

4.6.3.3 Modifications in LCC inverter control for the PHC option

Here, as discussed in section 3.15.1, the LCC has current, and gamma control modes. As for the SHC (Section 3.14.1), these control modes are a little different from conventional LCC.

4.7 Smooth transition between the controller's outputs

The transition between control modes is made to achieve SHC-, and PHC-LCC characteristics (Figure 4.3).

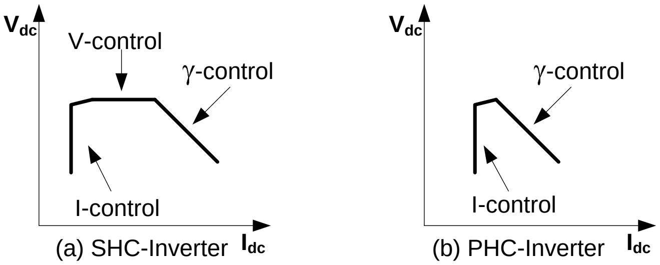

Figure 4.3 LCC hybrid inverter control transition modes

The transition for SHC is implemented by the controller of Figure 4.4(a), where the error generated by the current, gamma, and voltage control loops is compared and the largest one is selected and acted upon by the PI controller. The PHC controller similarly generates the error signal using current and gamma control loops, as in Figure 4.4(b). The single PI unit ensures that there is no sudden change in the inverter α -order (AOI), when controllers are selected / deselected.

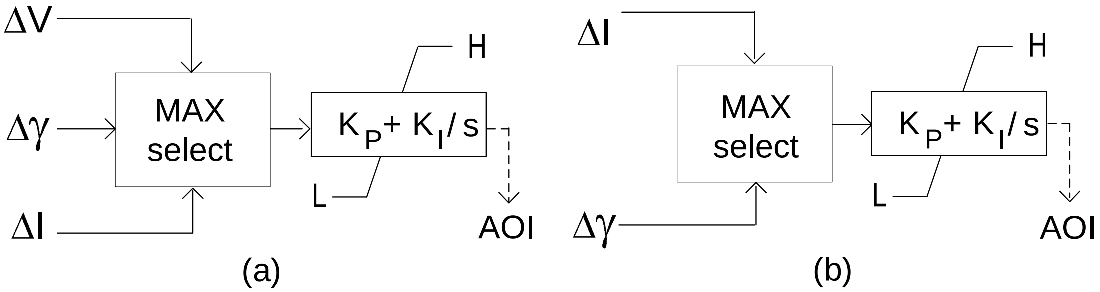

Figure 4.4 Smooth control transition mechanism for (a) SHC and (b) PHC options

Earlier schemes that used two or more separate PI controllers for each control loop suffered from the drawback that the deselected controller would go into saturation, thereby not allowing it to take control immediately where needed. The single PI unit also avoids this issue because it is never deselected.

4.8 Analysis of hybrid system performance

In this section the simulated results for the operation of the hybrid HVdc alternatives are presented. Several different studies were carried out, and a few candidate results are presented here. To assess the hybrids' robustness under small and large dynamic disturbances the performance of the hybrids and that of a conventional LCC based system (the unmodified Cigré Benchmark model) are compared through simulating their performances following dc, and ac side faults with varying severities. The numerical simulation on an electromagnetic transients (emt) solver was conducted to assess the behavior of the converters and the interconnected ac and dc networks. The particular emt program used in this study was PSCAD/ EMTDC.

4.8.1 System Steady-State Operation

Following the start up (Section 4.5) both of the hybrid inverter systems will settle in their steady state points, verifying the designs (Appendix A). The Cigré Benchmark system cannot operate under such extreme low SCRs and does not have an equivalent steady state condition.

4.8.2 Dynamic response to step changes

Power systems are always prone to voltage disturbances, and these disturbances may generate other types of system disturbances. As a result, testing a system in order to study its response to a power or voltage step reveals useful information about system dynamic behavior and its performance under such conditions. The result is changes in two parameters of inverter terminal real power and ac voltage are of special interest. To investigate both hybrid system responses to small set point changes a sequence of equal magnitude step-down/step-up in power order was applied. The effect of step changes in dc current reference and ac system relative strength (SCR) are also studied. Small dynamic changes in VSC dc voltage reference will not be looked at, because based on the implemented control method (Section 3.11) this dc voltage is not variable and has a fixed reference point.

4.8.2.1 Dynamic response to step change in power order

To investigate both hybrid system responses to small power set point changes, a 10% step-down followed by a subsequent 10% step-up in power order was applied to their ordered signals. This step change is applied directly to the power order in SHC option; For the PHC case this step change is applied proportionally to both the LCC inverter and the VSC set points.

Figure 4.5 shows the SHC, PHC and LCC-only options' responses to the mentioned set point changes. The power order step-down is applied at 0.1 second, followed by the step-up at 1.1 second. The real power terminal, inverter and rectifier terminal rms ac voltage for all of the three options is plotted in Figure 4.5(a)-(c), respectively.

In the SHC option, the power order change is communicated via the change of current order to the rectifier. Here the LCC-inverter and VSC both carry the same current; the VSC maintains rated voltage on its ac busbar as well as rated voltage across its dc terminals. This results in sharing the power change by the LCC-inverter and VSC converters, in proportion to their relative ratings (Table C-3). Based on Figure 4.5(a), the real terminal power reduction and its subsequent restoration to full magnitude for the SHC option is achieved rapidly with no significant oscillation.

For the PHC option, the power order change is communicated through splitting the total current order of the LCC-inverter and VSC parts into individual current orders, in proportion to their designed ratings. The restoration to full power for the PHC is poorer, showing oscillation and lasting for approximately 400 ms (Figure 4.5(a)).

The LCC-only option also has a fast dynamic response, but demonstrates more overshoot, accompanied by fast oscillations, compared to the hybrid options. However, it must be noted that the LCC option is unable to operate into the inverter ac network with low SCR that hybrid inverters are connected to, and it has been assumed that the SCR has been increased to 2.5, by adding synchronous compensators, or other reactive compensations devices. For this option, the power order change is communicated, in the conventional manner, by dividing the power order by the inverter side voltage and passing the result as the rectifier current order to the rectifier.

As the VSC in SHC is capable of reactive power generation and is tasked to maintain the inverter ac terminal voltage ($V_{ac,Inv}$) at a constant level, the voltage returns to its pre-fault magnitude very rapidly, as shown in Figure 4.5(b), after applying the power order change, which shows almost no sign of overvoltage. The PHC also regulates this voltage, but the dynamic response is poorer. With the LCC-only option, the ac voltage is poorly regulated and rises to about 10% overvoltage as the load is reduced; this is not far from expectations, as no controller is aimed to regulate this voltage. As can be seen from graphs of Figure 4.5 both of the hybrid options can track the power order changes while

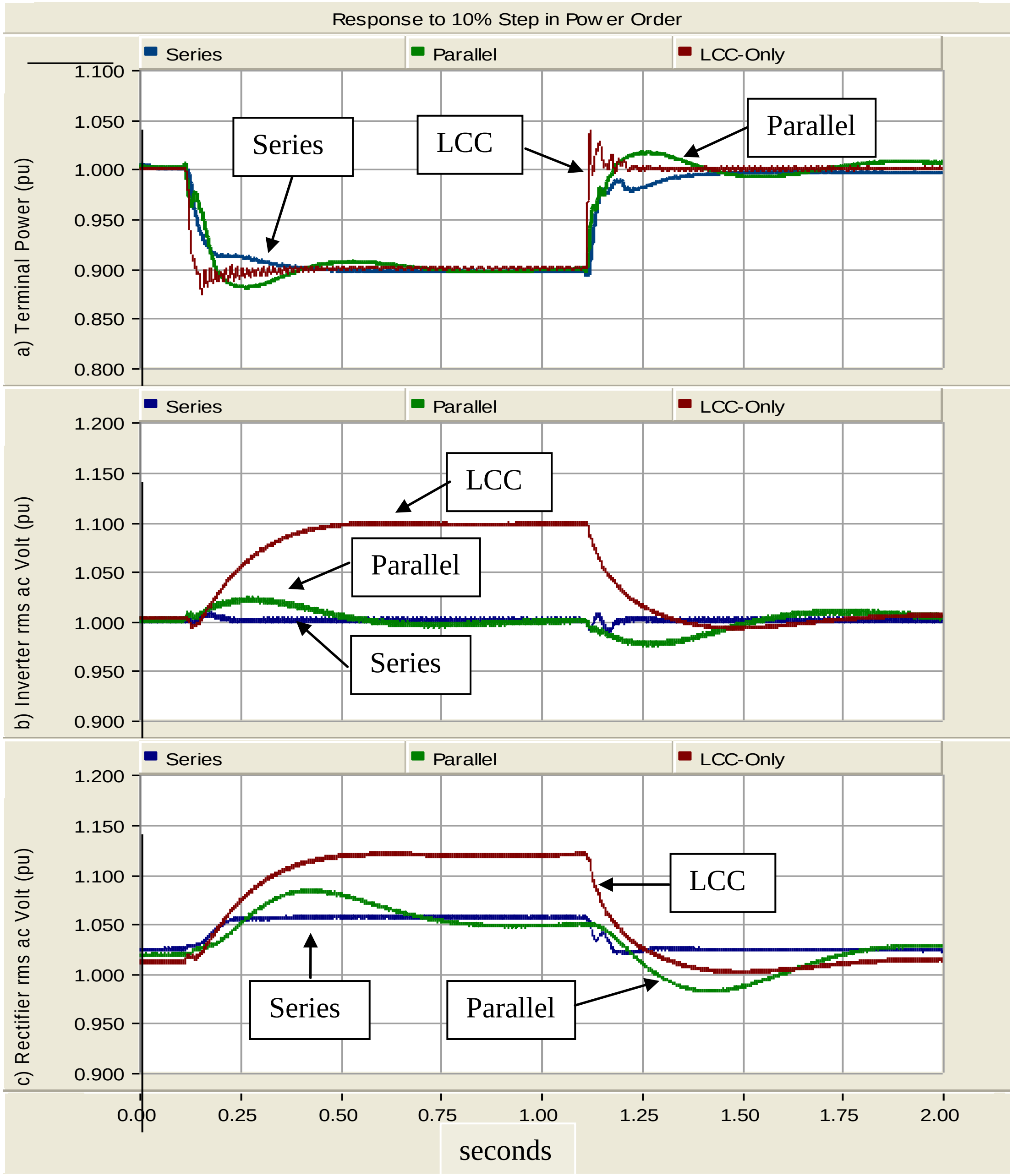

Figure 4.5 Small dynamic disturbance response to step change in power order

maintaining the rated ac side voltage. The performance of the SHC inverter, however, is much superior.

For rectifier rms ac terminal voltage changes ($V_{ac,\mathrm{Rec}}$) in all three cases behave very similar and smoothly, as shown in Figure 4.5(c). Overall, as can be seen from graphs, both hybrid options show quick, and well damped responses to the small power set-point changes.

4.8.2.2 Dynamic response to rectifier dc current order

To investigate the systems’ performance when the rectifier dc current is changed, a 5% step down followed by a 5% step-up in dc current is applied to rectifier dc current signal at 0.1, and 1.1 seconds, respectively, after system has settled down. In Figure 4.6(a) and (b) the ac inverter terminal real power and rms ac voltage is plotted, respectively.

As evidenced by the graphs, the terminal real power behaves very well for all of the three cases, though the PHC has a little oscillatory behavior, as shown in Figure 4.6(a). For the hybrid options the inverter rms ac voltage has almost no visible disturbance because of fast VSC voltage correction. In the LCC-only case corrective action is missing because no controller has been assigned for such correction.

As can be seen from the figures, both of the hybrid options can track the power order changes while maintaining the rated ac side voltage. The performance of the SHC inverter, however, is much superior.

4.8.3 System response to inverter side short circuit ratio changes

To simulate the effect of sudden changes in ac-side configuration such as line insertion / removal or adding/subtracting generating capacity, a step change in the short circuit ratio of the ac system was applied. The ac-side short circuit ratio at the inverter side is increased by 25%, from SCR = 1 to SCR = 1.25 at t = 0.1 second; then later, at t = 1.1 second, the short circuit ratio is lowered back to SCR = 1. The dynamic effects of these changes are plotted in Figure 4.7(a)-(c), wherein inverter ac terminal power and rms voltage, along with the extinction angle (γ) are seen, respectively. During this change the Thevenin voltage source magnitudes are adjusted so as to keep the steady state terminal voltage at unity.

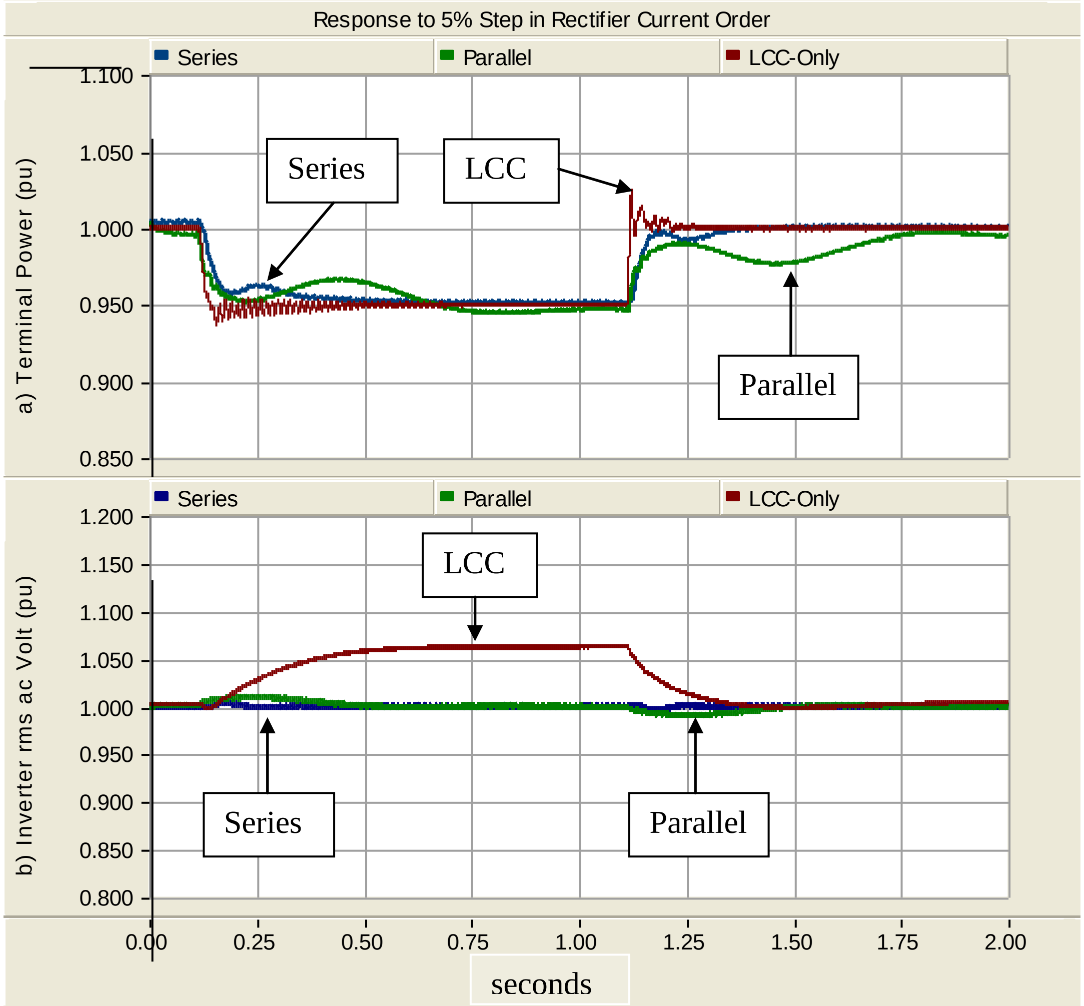

Figure 4.6 Response to step change in rectifier dc current order

From Figure 4.7(a)-(c), which show the inverter terminal real power, rms inverter ac voltage and excitation angle, respectively, it is evident that the series hybrid option has a faster well-damped transient performance compared to the parallel hybrid option.

4.8.4 Inverter load rejection

An HVdc-converter normally consumes reactive power of around 0.5 - 0.6 p.u. of its real power rating, both when operating as a rectifier or as an inverter. A major part of this reactive power is provided by the harmonic filters and dedicated shunt capacitors. The amount of reactive power consumed at the converter bus also increases with an increase in the firing angle in rectifier, or in the extinction angle in inverter.

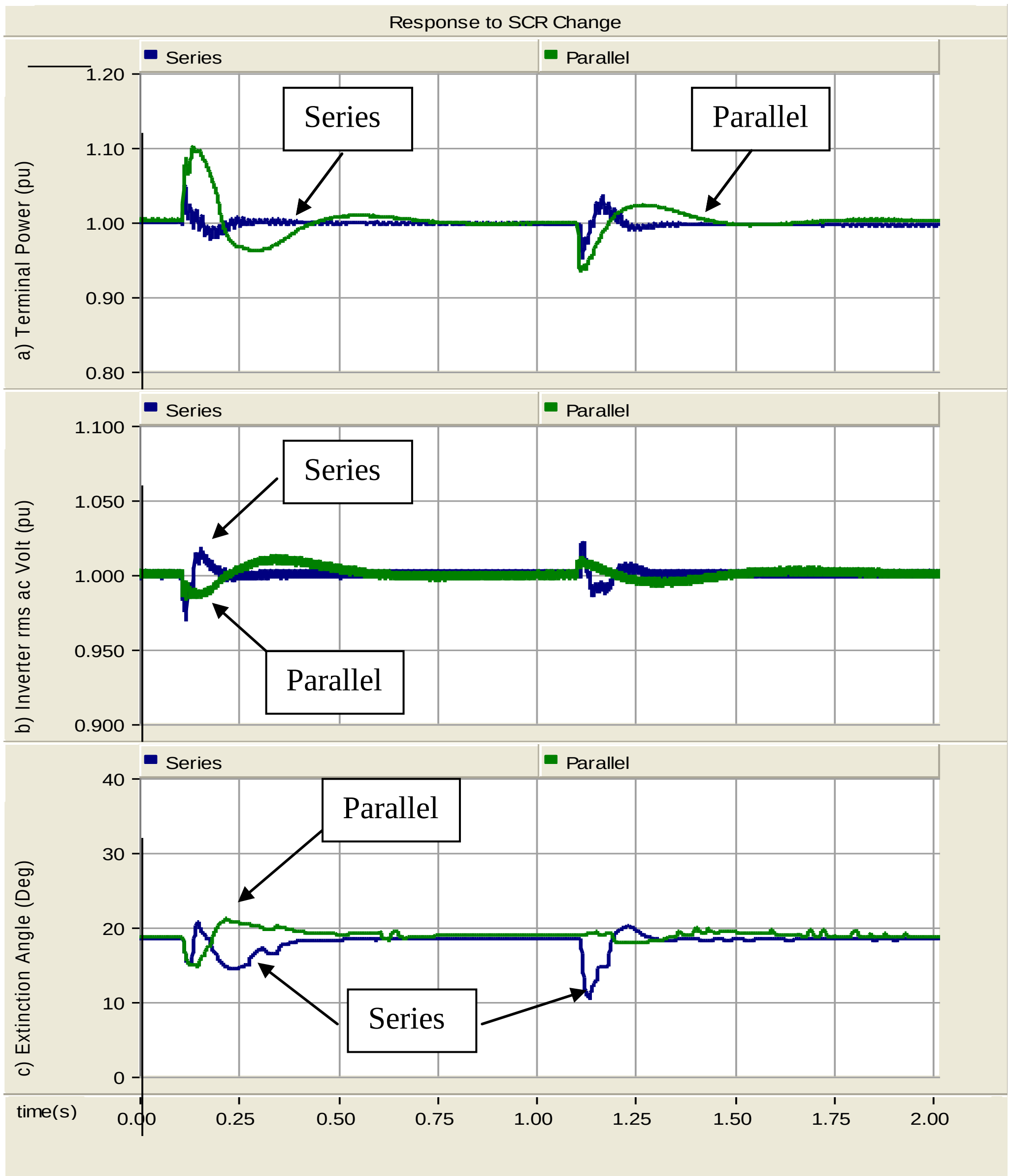

Figure 4.7 Step change in ac system short circuit ratio (SCR)

The corresponding reactive power supply in the hybrid options is negligible. This is due to its ability to internally generate reactive power using the VSC converter. The installed Mvar in harmonic filters is thus significantly less at the hybrid inverter options compared to the LCC-only option, as described in section 3.9.1.

If the transmitted dc power is suddenly decreased, (for example because of load rejection), the reactive power consumed at the LCC-inverter bus will drop correspondingly, which will temporarily raise the ac inverter bus voltage. As soon as the VSC controls respond and increase the modulation index (m), the excessive generation of reactive power will be stopped and terminal voltage will be adjusted. Part of this temporary overvoltage may also be adjusted using exciter intervening of ac system generators, if they are in sufficient proximity.

The load rejection voltage (V_{LR}) can be calculated theoretically, simply using the ac network voltage magnitude, the impedance of the network equivalent and the total harmonic filter impedance at fundamental frequency, as:

$$V_{LR} = V_{sys} \frac{Z_f}{Z_f + Z_{sys}} \tag{4.1}$$

where V_{sys} refers to ac-network voltage magnitude and Z_f and Z_{sys} refer to total harmonic filter impedance and equivalent system impedance, respectively. The theoretical overvoltage for a 1000 MW LCC-only based HVdc system having a SCR = 2.5 using 620 Mvar reactive power generation will have an approximate overvoltage magnitude of 25% in steady state. This number was verified through simulation and the observed overvoltage was around 22%. If such a LCC-only based system is able to work under SCR = 1, the steady state magnitude of the calculated overvoltage will be equal to around 62%. If the reactive power generation can be lowered to around 100 Mvar, the overvoltage would be around 10%.

On the other hand, with the assumption of a hybrid inverter system (series or parallel inverter based) with 1000 MW dc power rating with total reactive power generation from ac filters of around 100 Mvar at the inverter side (for SCR =1), the steady state magnitude of the calculated overvoltage will be 10%, given no intervening from the VSC converter. In practice, the VSC would interfere and change the scenario.

In Figure 4.8 the inverter rms ac voltage response to a complete (100%) inverter load rejection is given. Comparing the graphs with the calculated numbers shows that results agree very well.

Simulation of the system (Figure 4.8) resulted in transient overvoltages of around 7% for the SHC and 2.5% for the PHC option, and zero steady-state overvoltage. The presence of the VSC converter lowers the load rejection overvoltage not only because of the need for smaller amount of installed reactive power converters (harmonic filters) at the inverter terminal bus, but also because of its ability to regulate reactive power through the VSC. It is concluded that regarding overvoltage performance, the hybrid converters have superior performance, even when they are connected to very weak ac systems.

4.8.5 Large signal response and fault recovery performance

The response of the SHC, PHC and LCC-only options to large dynamic disturbances in the form of ac and dc faults was investigated. All categories of ac faults (3, 2, and single phase faults to ground) with a wide range of fault impedances were applied to inverter and to rectifier terminals for a period of 0.1 second (6 cycles). The results are discussed in the following sections.

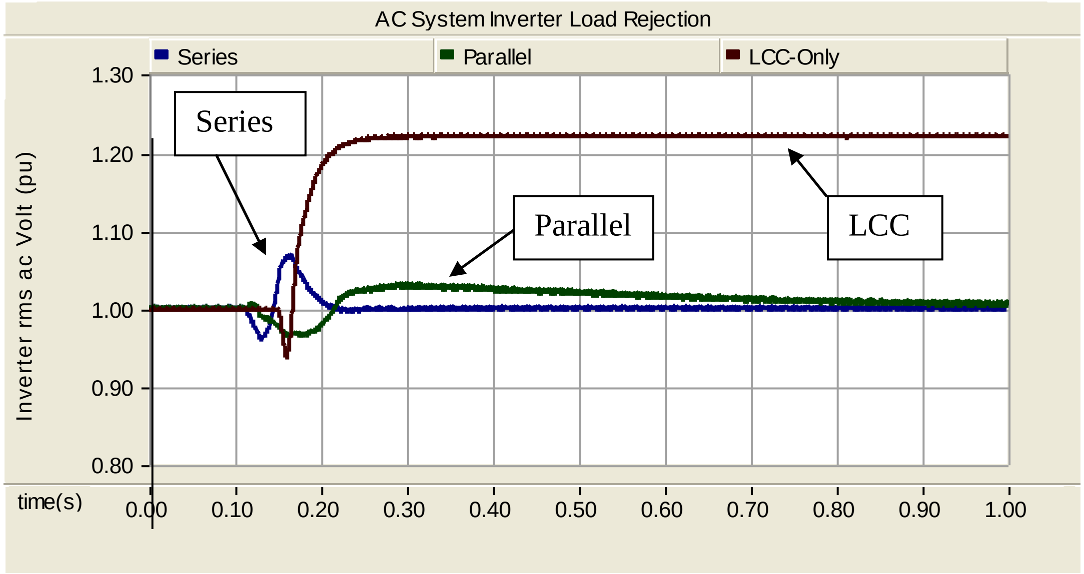

Figure 4.8 Overvoltage following an inverter load rejection

4.8.5.1 Three-phase ac inverter-side faults

Applying a three phase (close-in) fault at the ac inverter terminal is one of the most critical tests to very weak systems. Such a fault effectively reduces the inverter terminal voltage to zero. To simulate the effect of this fault a 0.005 p.u. inductance was shunt connected to the ac inverter terminal for 0.1 seconds. The inverter terminal power, inverter side rms ac voltage, and extinction angle (γ) for the both hybrid options and the LCC-only option are shown in Figure 4.9(a)-(c), respectively.

As seen from Figure 4.9(a), the power recovery of the SHC option to 90% of the nominal power takes around 250 ms, which is nearly identical to the LCC-only option. Note that the LCC-only option has by necessity, a larger ac system SCR of 2.5 (as mentioned earlier operation at SCR = 1 is not possible for the LCC option), whereas the SHC has a much weaker ac system (SCR = 1). This shows that in comparison with LCC-only technology, the SHC option can achieve comparable performance even with short circuit ratios which are significantly smaller. For the PHC option, however, the recovery period is significantly longer with recovery to 90% power taking approximately 450 ms. Such long recovery times are a major drawback of PHC converters (Section 4.9). During the ac inverter fault the VSC capacitor discharges completely, and must be recharged during the recovery process, thereby extending the recovery time. The same delay is observed in the recovery of the ac inverter terminal voltage when comparing the PHC option with the SHC option, shown in Figure 4.9(b).

The extinction angles of the LCC converter for hybrid options are shown in Figure 4.9(c). Following the fault clearance, the SHC option shows quick recovery without further commutation failures and the extinction angle settles to its steady state value of 18^{o}. Again, the performance is virtually indistinguishable from the LCC-only option which has a 2.5 times larger SCR. In keeping with the observations of Figure 4.9(a) and Figure 4.9(b), the extinction angle of the line commutated part of PHC recovers more slowly.

It must be mentioned that in a number of faults, even with bigger fault inductances, the hybrid options might experience a complete transient power loss but commutation failure will not happen in their LCC converter, despite their very low SCR, while the LCC-only option will experience both the power loss and commutation failure.

4.8.5.2 Three-phase ac inverter-side remote faults

A remote fault is defined as a fault occurring electrically distant from the converter bus. The fault impedance is essentially that of the transmission line from the ac bus to the point of system coupling, and is primarily inductive. It is simulated by connecting a shunt reactor at the inverter bus. Faults with a wide range of inductances, varying between 0.01 and 5 p.u. were tried. In general, the bigger the fault inductance (i.e. the farther the fault),

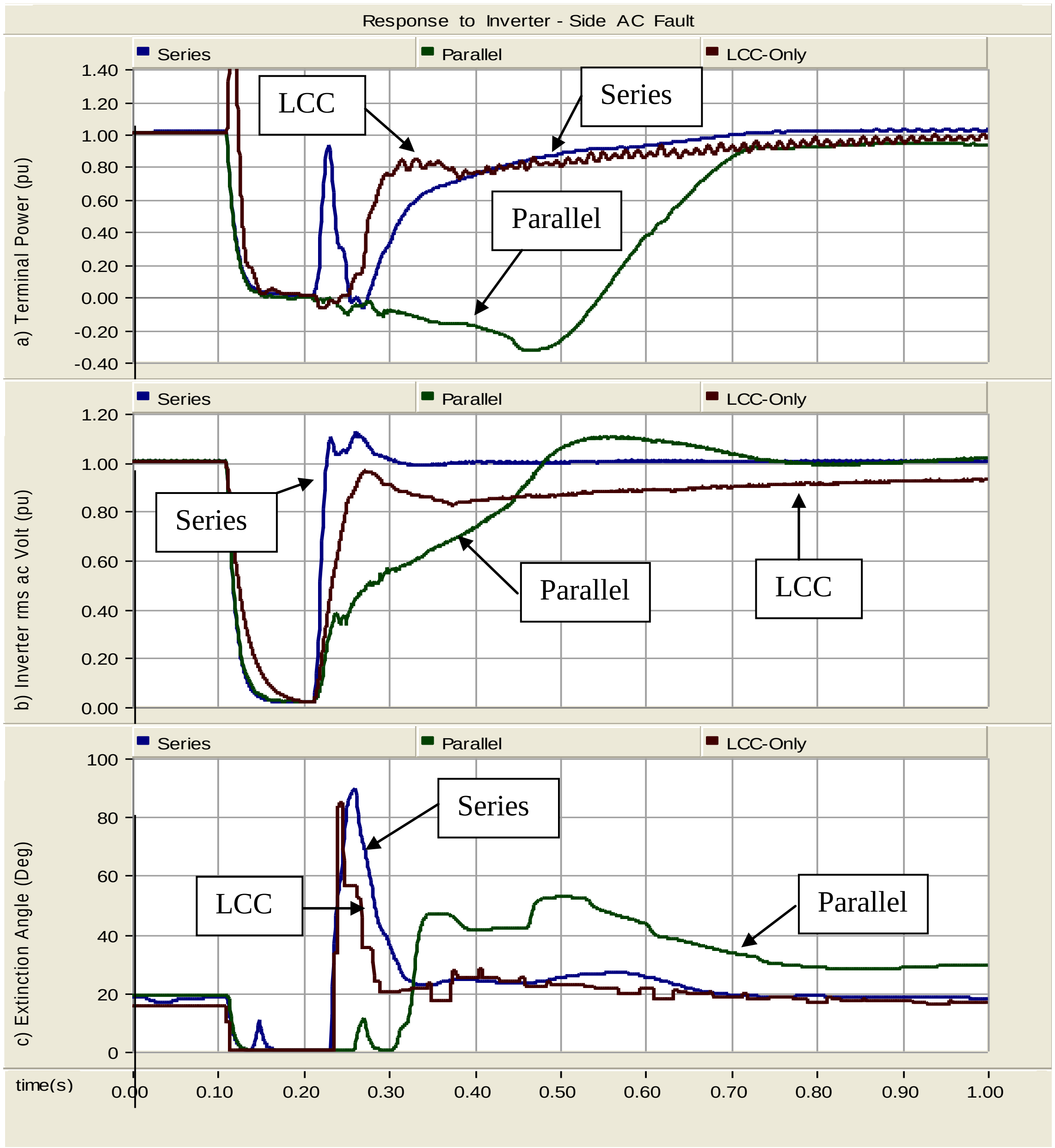

Figure 4.9 Three-phase inverter-side ac fault

the faster the recovery of real power and ac inverter terminal, and the less the chance of commutation failure. In Figure 4.10(a)–(c) the real power terminal and rms ac voltage, along with the extinction angle (γ) behavior of each of the SHC, PHC, and LCC-only options are plotted, respectively. These sets of graphs are derived based on applying a fault inductance of 1 p.u. for 0.1 seconds for all of the mentioned systems.

As seen in Figure 4.10(a), the terminal real powers are much disturbed for all of the cases. The series option has, on the other hand, excellent and rapid power recovery in around 150 ms after fault clearance. Again, the parallel option has a long power recovery time of around 600 ms, as discussed in 4.8.5.1. At around 370 ms, another commutation failure occurs in the LCC-only converter, temporarily bringing terminal power to zero.

The ac inverter terminal voltages are moderately disturbed, with the lowest voltage drop for the SHC and the most affected one being the PHC. The LCC-only option lies in between these two extremes Figure 4.10(b). The series hybrid converter undergoes an ac rapid voltage recovery in comparison with other options.

From Figure 4.10(c), the hybrid inverters and LCC-only option experience commutation failures. However, the SHC option recovers most rapidly. The LCC-only option starts to recover, but another commutation failure happens in the LCC converter.

Changing the fault duration time between around 50 to 200 ms did not cause any distinctive change in general systems' transient behavior but it has an impact on the recovery performance. Hence in conclusion the SHC option has a superior behavior in power recovery and re-adjusting its ac terminal voltage and its extinction angle.

4.8.5.3 Single-phase ac inverter-side faults

The same conclusion regarding fault performance can be drawn when a close-in single-phase line-to-ground fault is applied at the ac inverter terminal. From the simulated recovery plots of Figure 4.11(a)-(c) which is based on a 0.005 p.u. fault inductance, system recovery behavior is very similar to the three phase (close-in) inverter-side ac faults. Again, the SHC has a very similar power recovery trend with the LCC-only case, but the PHC undergoes an erratic and unacceptable terminal power

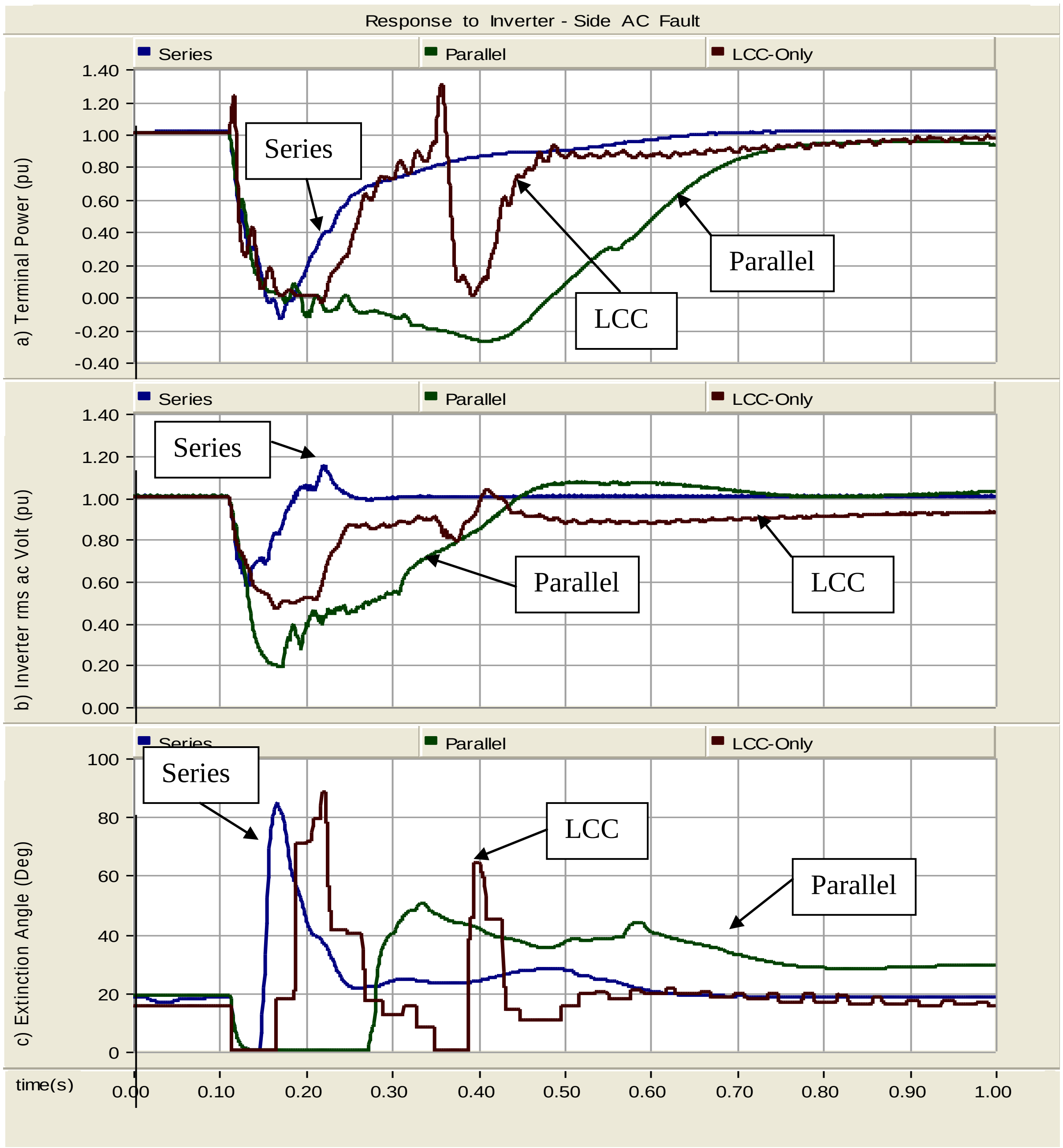

Figure 4.10 Three-phase inverter-side remote ac fault

recovery of around 600 ms (Figure 4.11(a)). Rms ac inverter terminal voltage would drop transiently, with the least affected one again being the SHC, and the most affected one is PHC option (Figure 4.11(b)). For the PHC option it takes more than a second to re-adjust its extinction angle (Figure 4.11(c)).

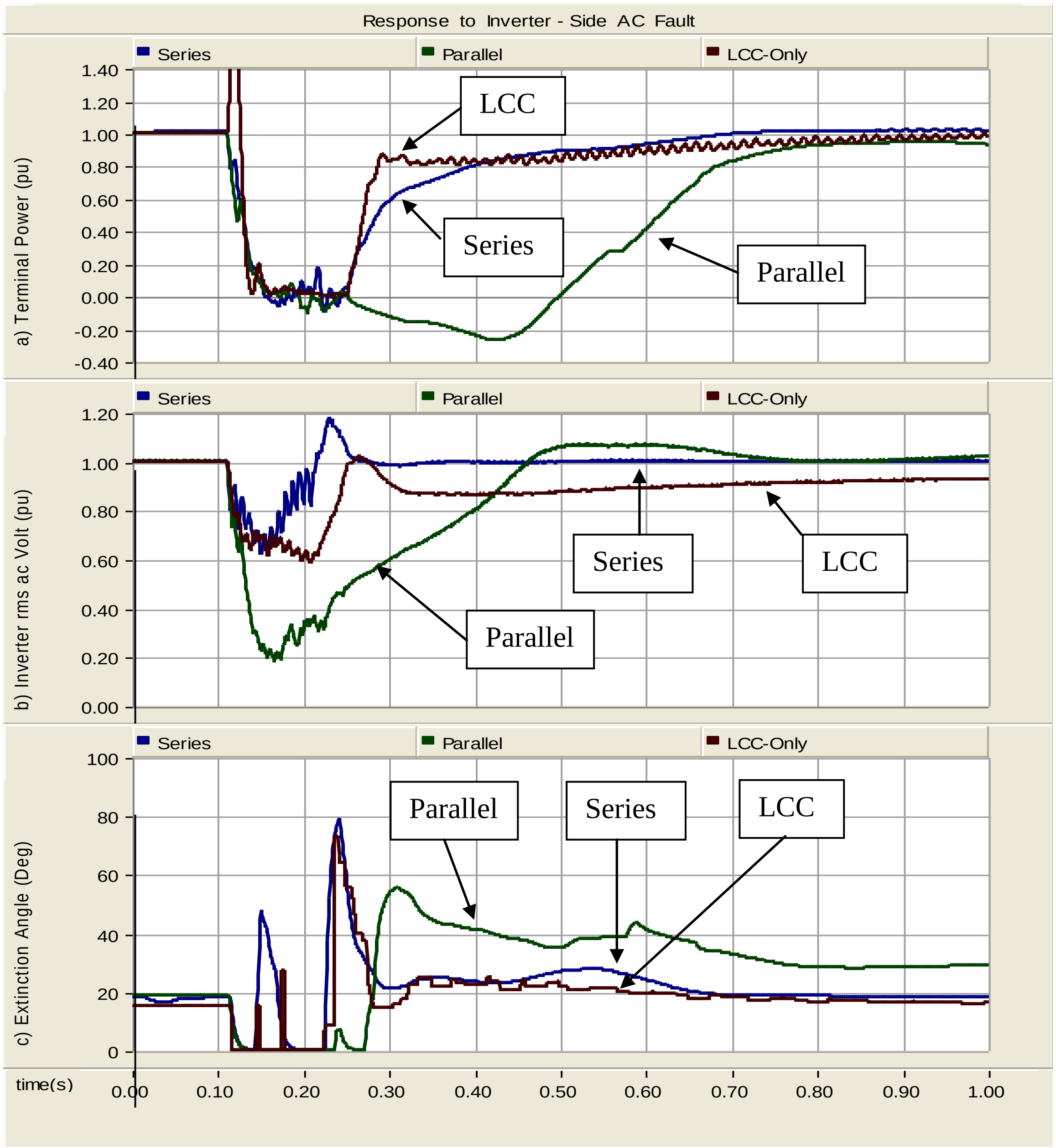

Figure 4.11 Single phase ac inverter-side close-in fault

Again the SHC option is able to recover quickly. It also appears that the LCC's recovery is fast, but it must be remembered that the SCR for the LCC had to be increased to 2.5, because it is unable to operate at the SCR = 1. Hence the SHC can be operated at a much larger ESCR with similar dynamic performance at a much higher SCR.

4.8.5.4 Single-phase ac inverter-side remote faults

Single phase remote-faults were simulated by connecting high inductive impedance from the ac inverter terminal to ground. A wide range of inductances in the range of 0.01-5 p.u. were tested. The overall system behavior was found to be very similar to the three phase fault case. The graphs are not shown here.

4.8.5.5 Three-phase ac rectifier-side close-in faults

In order to study the hybrid system performance in response to close-in three-phase faults at rectifier terminal, 0.001 p.u. impedance was applied to an ac rectifier terminal for 0.1 seconds. Such a fault effectively reduces the rectifier terminal voltage to zero. The simulated results for terminal inverter power, rms inverter and rectifier ac voltage, and extinction angle (γ) for both of the hybrid options and the LCC-only option are shown in Figure 4.12(a)-(d) respectively.

The transient behavior during inverter terminal power recovery is similar for the hybrids, and the LCC-only option. The LCC has faster overall power recovery (Figure 4.12(a)). Inverter ac terminal voltages for the both hybrid options are disturbed temporarily (Figure 4.12(b)). The SHC shows an overshoot of around 15%. Both of the hybrid options settle in less than 50 ms. The LCC-only option does not demonstrate any overshot, but settles very slowly. The rms rectifier ac voltages for all of the options settle in around 150 ms (Figure 4.12(c)).

In Figure 4.12(d) the extinction angle behavior for the three options is shown The LCC-only option has a poorer response in the sense that commutation failure was almost happening.

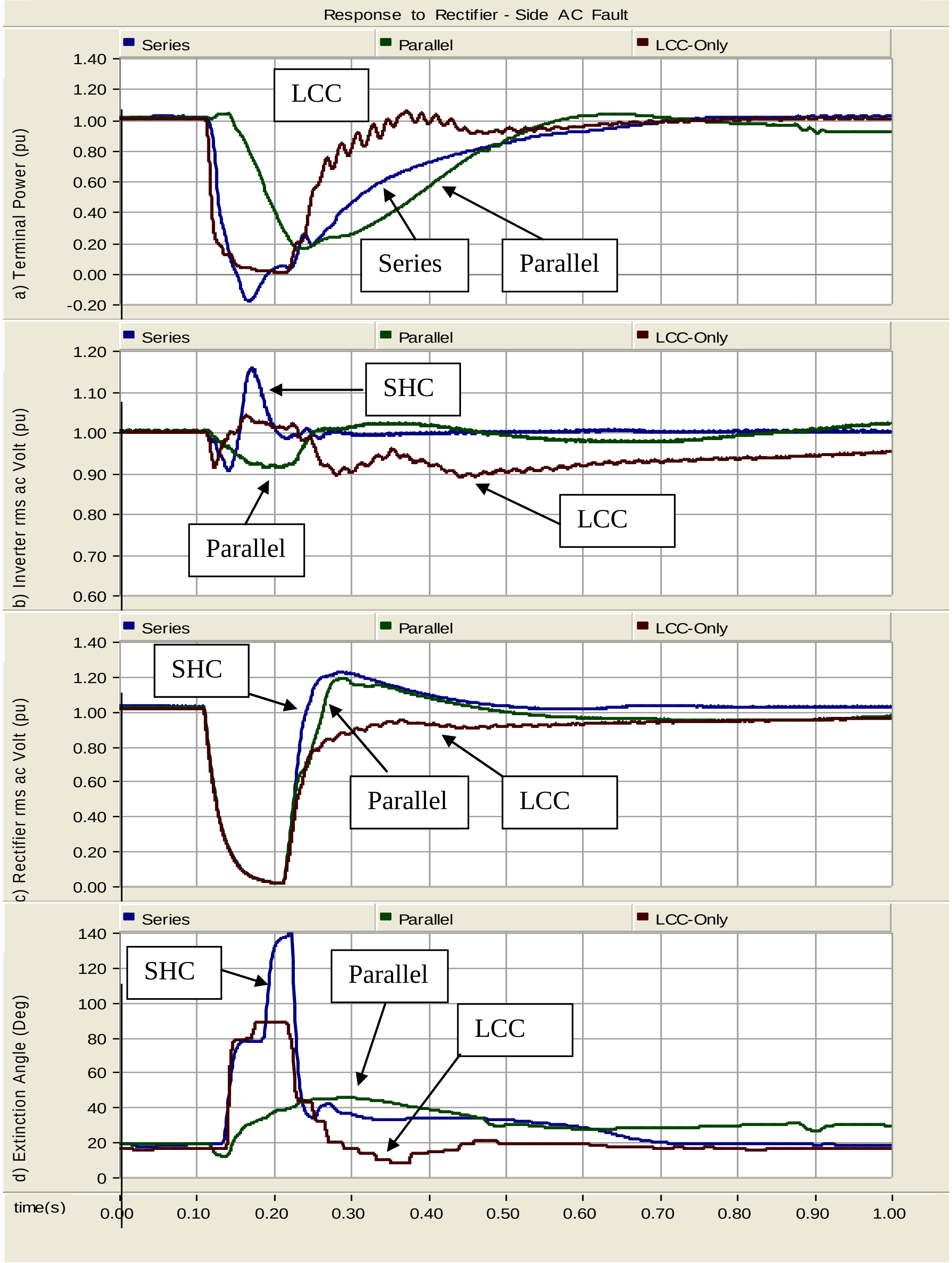

Figure 4.12 Three phase ac rectifier-side close-in fault

4.8.5.6 Three-phase ac rectifier-side remote faults

Remote faults in the rectifier ac bus were applied using different magnitudes. The graphs of Figure 4.13(a)-(d) were simulated using a 1-p.u. inductance. Here, the inverter terminal real power, rms inverter and rectifier ac terminal voltages, and extinction angle behavior for both of the hybrid and LCC-only options are plotted, respectively.

The transient behavior during inverter terminal power recovery is similar for the hybrids, and the LCC-only option. The LCC has faster overall power recovery (Figure 4.13 (a)). At around 300 ms, another commutation failure occurs in the LCC-only converter, temporarily bringing terminal power to zero.

In response to the applied fault, the inverter ac terminal voltages of the series and parallel options demonstrate overshoots of 15% and 10%, , respectively, but settle in less than 100 ms. For the LCC-only option, however, an overshot of 10%, followed by a settling time of longer than one second is observed (Figure 4.13 (b)).

The rectifier fault causes almost equal rectifier voltage drops in both of the hybrids followed by 20% terminal transient overvoltage, which settles to its steady state in around 200 ms. The LCC-only option drops much more, to around 40%, but does not suffer from a significant overvoltage. It takes more than a second for the rectifier terminal voltage to settle to its nominal voltage (Figure 4.13(c)).

It is worth mentioning that neither of the hybrid options demonstrates a commutation failure during or after fault clearance. The LCC-only option, on the other hand, experiences a commutation failure after fault clearance (Figure 4.13 (d)). It can be concluded that both of the hybrid options are more immune to commutation failure during such ac rectifier side faults.

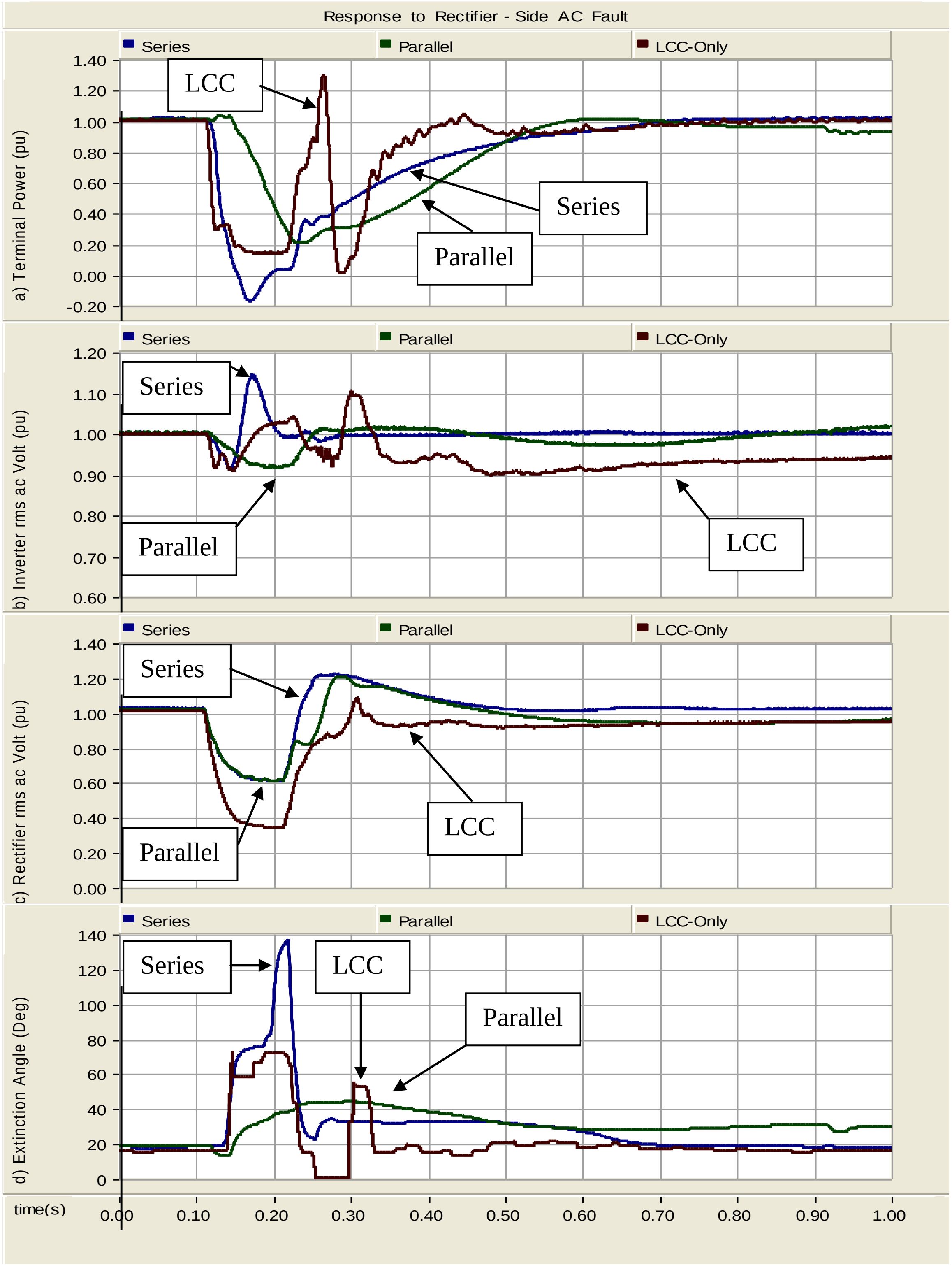

Figure 4.13 Three phase rectifier-side ac remote fault

4.8.5.7 Single-phase ac rectifier-side faults

Behavior of both hybrid options, and LCC-only option in response to close-in, and remote rectifier-side ac single phase faults have very close similarity to the 3-phase fault recovery behavior; the only difference being that, using equal p.u. fault inductance, single phase ac faults cause less disturbance compared to the three-phase fault cases for both the hybrid inverter options, and LCC-only option. Also it was observed that the inverter terminal experiences less voltage drops and the considered systems generally have less chance of commutation failure. The graphs are not shown here.

4.8.5.8 Dc fault at rectifier/inverter side

As will be discussed in section 4.9 any dc fault on a dc transmission line causes a short circuit across the VSC capacitor. This problem can be solved by opening the ac circuit breaker in front of the VSC converter which will stop the fault from being fed through the VSC diodes. An alternative solution is to use a dc circuit breaker in series with the VSC. It is expected that such breakers will be available in the near future; however, dc circuit breaker based arrangements are not considered in this research.

A solid dc fault with 0.01 ohm resistance was applied to the inverter dc terminal for 0.1 second. Recovery from dc faults requires the rectifier to temporarily go into inverter mode and thus de-energize the line, referred to as ‘forced retard’ [5]. Here it is assumed that the line is an overhead line and using this method may be justified; in case of a cable, such dc voltage reversal may not be possible. It needs to be emphasized that for the PHC option clearing any dc fault also requires the VSC breaker to be opened as will be explained in section 4.9. The graphs in Figure 4.14(a)-(c) represent ac power and rms inverter terminal ac voltage and the LCC extinction angle, respectively.

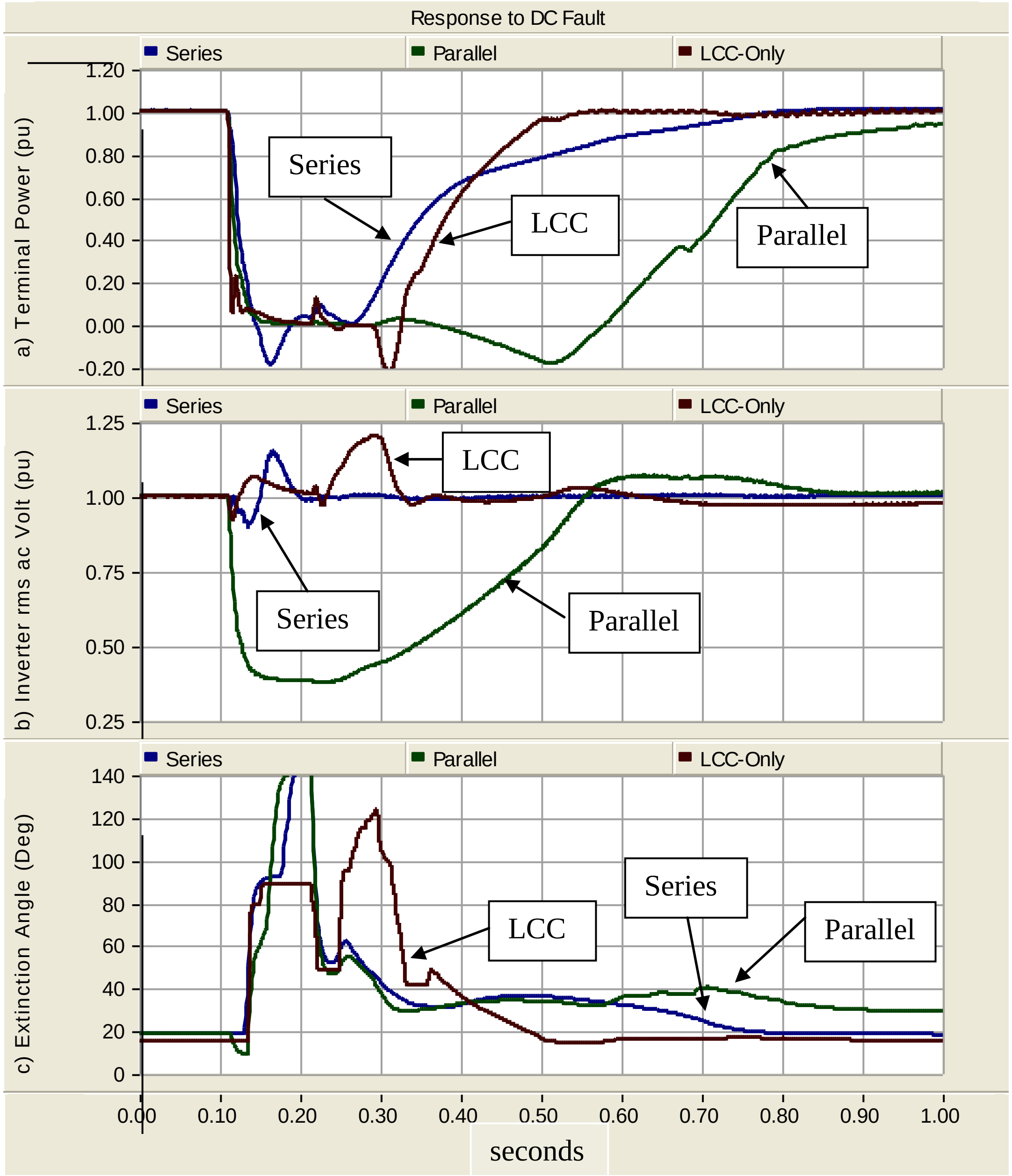

Figure 4.14 Dc fault at inverter dc terminal

The system response to dc faults at inverter and rectifier sides are the same. Based on the ac voltage response at the inverter terminal (Figure 4.14(b)), it can be stated that during dc faults, the PHC option is unable to properly control the ac terminal voltage. This is a weakness of this hybrid option, in comparison to the SHC option.

4.9 Intrinsic drawback of parallel hybrid converters (PHC)

Any ac fault applied at the inverter side which causes commutation failure will eventually end up with a LCC converter bypass operation that effectively demonstrates a short circuit across the VSC capacitor (Figure 4.15). This results in a short circuit current with contributions from the discharging capacitor as well as the ac system through the VSC diodes, assuming that the ac voltage will not drop to zero. The LCC converter is unable to recover and resume normal operation as long as the VSC continues feeding the bypass loop completed through two thyristors, such as thyristors 6 and 3 (Figure 4.15). This is because the dc current supplied through VSC is much larger than the nominal dc current. This situation is even worse in a system with low SCR. In such case the VSC (now behaving like a diode bridge) absorbs large amounts of reactive power while feeding the short circuit. This in turn causes a substantial drop in ac voltage which also makes it more difficult for the LCC inverter to recover.

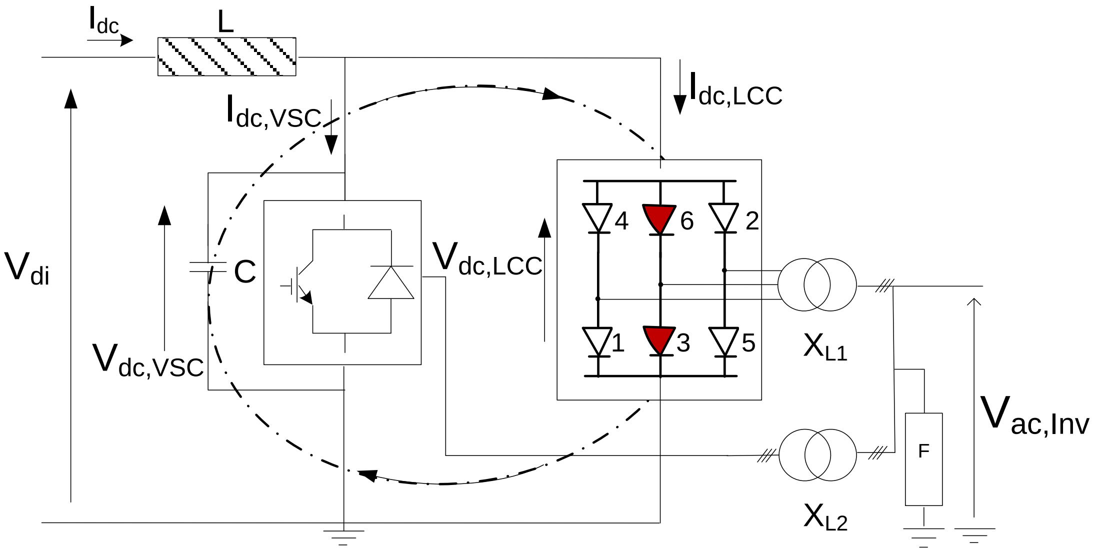

Figure 4.15 Circulating current in PHC option during an ac inverter-side fault

A similar problem exists when a fault on dc transmission line causes a short circuit across the VSC capacitor. This problem can be solved by opening the ac circuit breaker in front of the VSC converter which will stop the fault to be fed through the VSC diodes. However, opening ac breaker will not stop the fault current immediately as the inductances involved in the circuit will maintain the fault current. These inductances can include the smoothing reactor or the transmission line inductance depending on the location of the short circuit and the details of the circuit arrangement. The fault current path is now closed through the VSC diodes (Figure 4.16). The fault current will gradually decay with a time constant determined by the inductance and resistances of the circuit. The operation of the converters cannot be restarted until the fault current is cleared, which may take many cycles.

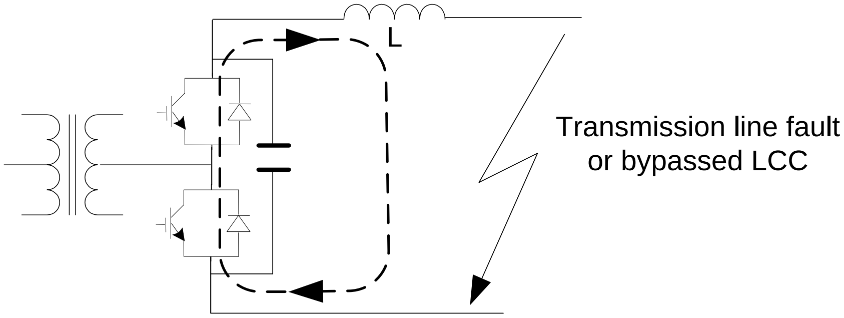

Figure 4.16 Circulating current in PHC option during a dc fault

The problem of prolonged restart time described above can be solved by a dc circuit breaker in series with the VSC. Mechanical dc circuit breakers are not yet commercially available but have been developed [95] and are expected to be implemented in real high power applications in near future [96]. Using this arrangement, HVdc link can resume operation after clearing the dc line or inverter side ac fault within a reasonable time, before the ac systems at two ends start falling apart.

A solid inverter ac fault at 0.01 seconds was applied to a PHC option. A commutation failure forms in LCC converter and a circulating dc current develops between the LCC and VSC converters (Figure 4.17(a)).

The specified currents for each converter are per-unitized independently, but have the same magnitudes. Based on the graph, the LCC and VSC converters draw enormous currents exceeding the acceptable transient current for each converter, through VSC's reverse diodes. It is assumed that based on intervening of a dc circuit breaker, the circulating current will be stopped. The total dc current flowing in the inverter and rectifier-side is plotted in Figure 4.17(b).

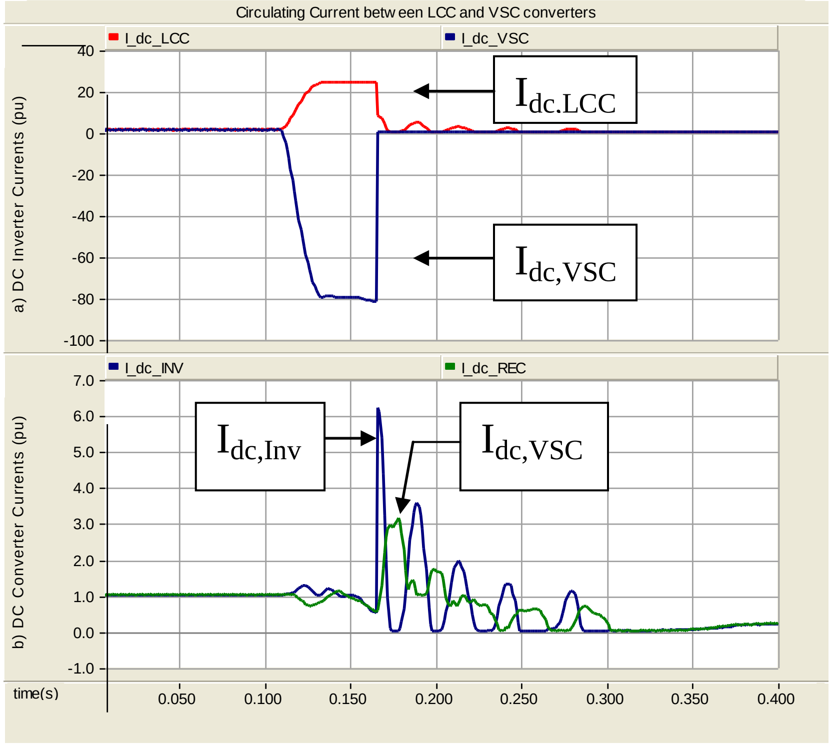

Figure 4.17 Circulating current between LCC and VSC converters in PHC option

4.10 Hybrid converter commutation failure performance

It is expected that the LCC inverter of the hybrid converter should be less prone to commutation failures in response to ac and dc system disturbances. This is because of the voltage regulation capability of the VSC-converter of the hybrid inverter. A performance index called the "Commutation Failure Immunity Index" (CFII) has recently been introduced to assess susceptibility of a converter to commutation failure [94]. The CFII is defined as the critical fault MVA divided by the dc power:

$$\text{Immunity Index} = \frac{V_{ac}^{2}}{Z_{fault}.P_{dc}}.100\% \qquad (4\text{-}2)$$

where $Z_{fault} = \omega.L_{\min}$. As can be seen, the larger the CFII, the smaller the magnitude of the fault required to create a commutation failure, and hence the larger the "immunity" of the converter to commutation failure. In this approach, an inductive fault is applied on the converter busbar and the commutation performance of the LCC is observed. The fault impedance is progressively reduced until commutation failure occurs, and the resulting fault MVA is referred to as "critical". Based on fault simulations, the CFII for the hybrid options and the Cigré Benchmark model was attained and is listed in Table 4-1. The results show that both of the SHC and PHC options are significantly more immune to remote faults compared to the LCC-only option (the Cigré Benchmark model).

Table 4-1 CFII for hybrid options and LCC-only case

Series Hybrid option	Parallel Hybrid option	LCC-Only (the Cigré Benchmark)	
SCR = 1	SCR = 1	SCR = 2.5	SCR = 4.6
24%	19%	14%	24%

For further comparison, the Cigré Benchmark (LCC-only case) was modified. To do this the SCR of the inverter system was increased until the immunity index of the LCC-only option, was the same as the SHC's immunity index. The resultant SCR value was 4.6.

Hence, it can be concluded that in spite of this fact that both of the hybrid options are extremely weak ac systems (SCR = 1), the hybrid options are able to attain a high level of immunity against commutation failure; whereas the LCC-only option would require a far stronger system (SCR = 4.6) to provide comparable performance.

4.11 VSC converters overcurrent protection

The LCC-based options have high over-current tolerance. They could be protected against fault-initiated over voltages using surge arresters, which is a normal procedure in HVdc converters. The VSC-based converters, on the other hand, cannot handle over-currents easily. A logic-circuit based method is developed and implemented here that protects the IGBT valves against overcurrent. This circuit has been implemented in both the series and parallel hybrid options. The description of how the method works is as follows.

The instantaneous ac phase current of VSC is compared with a reference value. If magnitude of this current is not exceeding the maximum allowed value, no corrective action is taken. If the instantaneous ac current exceeds the maximum allowed value, the IGBT valves for the corresponding phase are ordered to switch their state, i.e. if the valve is conducting it is switched off, and vice versa. Now because the conducting IGBT is substituted with an IGBT on the opposite leg of the same phase, the current on that phase is limited. The corresponding PSCAD logic circuit drawing is given in Figure D-3.

Chapter 5: Concluding Remarks

5.1 Introduction

The contribution of this thesis is the demonstration of the feasibility of VSC-LCC hybrid converter arrangements for High Voltage direct current (HVdc) transmission systems in stations where support of ac voltage is mostly absent (very weak ac system). A feasibility study performs the analysis, and provides the information to help decision making for applicability of a proposed scenario.

In this thesis, a new approach is proposed in which hybrid configuration of VSC (Voltage Source Converter) and LCC (Line Commutated Converter) have been used. These hybrids are arranged in two separate forms of series and parallel connection of one VSC, and one conventional LCC converter.

Conventional converter technology (LCC) requires stiff ac voltage and enormous amounts of reactive power at the point of common coupling to operate; VSC converter-based HVdc schemes, on the other hand, maintain most of the advantages of conventional LCC-based systems. They have overcome a number of disadvantages inherent to conventional LCC systems. Their ability to provide voltage support to very weak ac networks through generating reactive power, while delivering real power, makes them an ideal option for providing reliable power to remote locations. On the other hand VSC converters suffer disadvantages such as higher costs, sensitivity to dc-side faults, higher losses, and smaller ratings in comparison to conventional converters.

Based on the appropriate control methods employed, combined with well tuned controller parameters, the proposed hybrid converters combine the advantages of individual VSC and LCC converters. At the same time, these new arrangements cover the disadvantages of using each converter individually.

In this thesis, simplified mathematical models and extensive effort on digital time domain simulation with PSCAD / EMTDC program is chosen as the method to tackle the achievability of the proposed hybrid converters.

Simulation results demonstrate the feasibility of employing series hybrid converters. This thesis concludes that the SHC configuration is a promising option to operate into a very weak ac system. Here, the VSC converter provides both the real power, and reactive power.

This thesis also concludes that based on Parallel Hybrid Converter’s poor dynamic performance and its intrinsic drawback of responding to dc and inverter-side ac faults, its application for transferring real power in very weak ac system conditions is not recommended.

In this chapter first the hybrid applications are discussed. Then in the following sections the performed tasks of the thesis is highlighted. Finally main contribution of the thesis and the recommended future directions are discussed.

5.2 Hybrid converter applications

Based on the investigations done in this thesis, the following possible applications for the proposed series and parallel hybrid converters can be categorized.

5.2.1 Using hybrid converters in a new HVdc design

A hybrid converter system can be used in a new HVdc transmission system:

In a new design, the dc system electrical parameters can be set first. In this case, the power rating of the VSC and LCC converters can be calculated optimally. Based on that, the most suitable voltage/current rating for each converter can be allocated. The hybrid-side electrical system can be connected to a very weak ac system.

5.2.2 Using hybrid converters as an upgrade in an HVdc design

Hybrid converters can be used as an upgrade in an existing LCC-only HVdc system: The upgrading can be done through the addition of a VSC unit; the VSC unit can be used to increase the level of transmitted power without the addition of extra filters or reactive power sources, as would have been required with a conventional LCC-upgrade. The two possible options are:

- Using the SHC topology to upgrade the converter voltage level by retrofitting a VSC in series connection with a working LCC converter. This requires upgrading of the dc side voltage rating of the dc transmission system.
- Using the PHC topology to upgrade the converter current level by retrofitting a VSC in parallel connection with a working LCC converter. This requires upgrading of the dc side current rating of the dc transmission system.

To upgrade an HVdc system that is already operating based on LCC-converter technology there are limitations on retrofitting a series, or parallel VSC converter. Most of these limitations emerge because of the existing level of voltages / and or currents available in the system, which might not be possible to change. Under such circumstances, using the proposed optimization scenario for selecting the optimal power, and allocating appropriate voltages (or currents) might not be possible. As such, most probably the retrofitted VSC cannot have optimally selected ratings.

5.2.3 Substituting part of a HVdc system with a hybrid converter

Part of an LCC-based HVdc system can be substituted with a VSC converter: There are parallel connected LCC converters already working in HVdc transmission systems. With decreasing trend seen in IGBT component prices, the VSC converters may be substituted by one LCC converter that has to be pulled off permanently from operation. One example of that could be retiring of one of the two LCC converter bi-poles in Manitoba province that are working in parallel, and substituting one of them with a VSC converter.

Paralleling a VSC converter with a conventional LCC converter, which forms a PHC converter, has already been discussed in this thesis. When dc breakers are commercially available to stop successfully the dc fault and inverter ac faults, a PHC might be an option. If the PHC is not serving a very weak ac system, this configuration might demonstrate acceptable dynamic performance. It must be stressed that as a finding of this thesis, the PHC application is not recommended for supplying a very weak ac electrical system.

5.3 Highlight of the performed tasks

This section highlights and discusses the performed tasks during this research. These include:

- Hybrid VSC–LCC converters in two configurations of series (SHC) and parallel (PHC) were proposed.
- A new optimization concept was introduced. In this optimization a suitable proportion of voltage between VSC and LCC converters for the SHC option, and a suitable proportion of current between the VSC and LCC converters for the

PHC option can be allocated. Upon using this concept, the most appropriate voltage and current levels for the corresponding hybrid converters can be obtained.

- Control methods necessary for system operation were distinguished and implemented successfully.
- Hybrid systems under very low short circuit ration conditions (SCR = 1) were simulated.
- System dynamic response to step changes in operational set points, and system dynamic response to different large disturbances under SCR = 1 were investigated and compared with the Cigré Benchmark model responses.
- The commutation failure immunity level of hybrid converters was calculated and compared with the Cigré Benchmark model.
- A logic circuit based method was proposed to protect VSC switches from over currents.

5.4 Conclusions and findings of the research

The conclusions and findings of this research are:

- The hybrid VSC-LCC converters are capable of working under very weak ac system conditions. As conventional LCC converters need stiff voltage to be able to operate under such conditions, they do not represent possible candidates to work under such circumstances.

Hybrid options:

  - Provide excellent voltage support at the inverter terminal, even under very weak ac system conditions. As the conventional LCC converters need such support, they cannot be used individually under such circumstances.
  - Demonstrate excellent small dynamic response to step changes applied in terminal real power and rectifier dc current order.
  - Demonstrate very good response to short circuit ratio changes.
  - Have low-overshoot response to full inverter load rejection, with zero steady-state overvoltage. It is concluded that regarding overvoltage, the hybrid converters have superior performance, even when they are connected to very weak ac systems.
  - Under very low short circuit ratios (SCR = 1) show very competitive dynamic performance compared to conventional LCC converters working under higher short circuit ratios (SCR = 2.5).
  - Exhibit much higher commutation failure immunity index (CFII) under equal short circuit ratio conditions. This means that hybrid options are less sensitive to remote faults. As a result the chances of commutation failure in the proposed hybrid converters are generally much less than the conventional LCC converters.
  - Show less sensitivity to single-phase faults, compared to LCC-only option.
- SHC option is a promising solution for feeding high power to very weak ac systems. The VSC can deliver an optimally-calculated real power share.

- PHC option is not a good candidate to work under very weak ac system conditions. This is because of its poor dynamic performance and its intrinsic drawback of responding to a group of faults.

5.4.1 Advantages of using the proposed hybrid converters

Based on the simulation results the series hybrid converters possess the following advantages, compared to the LCC-only converters. They demonstrate:

- fast and well-damped response to power step, and rectifier current order changes
- less chance of total power disruption
- less inverter terminal voltage disturbances compared to conventional LCC converters
- less overall system impact during faults
- less sensitivity to single phase-to-ground faults
- operating under de-rated mode when LCC inverter has failed to operate
- generally much less susceptibility to commutation failure following ac rectifier faults compared to conventional LCC converters
- having higher commutation failure immunity index (CFII)

5.4.2 Disadvantages of using the proposed hybrid converter options

Based on the simulation results the parallel hybrid converter suffers from an intrinsic drawback that during ac inverter-side faults, or dc faults, the fault current cannot be easily interrupted and demonstrates long power recovery time. It has also generally poorer dynamic performance compared to LCC-only converters.

Other weaknesses of the proposed hybrid options are:

- Changing the direction of power flow in hybrid options is complicated and may need complete shutdown; shutting down itself depends on the method used.
- To shift the low order harmonic content to higher frequencies and avoid using expensive low-order harmonic filters, the switching frequency of forced commutating components must be selected high, which causes higher power losses during the switching times.
- They need at least one more transformer compared to the LCC-only converters.

5.5 Main contributions of the thesis

The followings are considered the key contributions of this thesis:

- A series hybrid converter composed from series connection of one VSC and one LCC converter was proposed, designed and simulated. It is shown that this converter is capable of operating into an electric system with very short circuit ratio (SCR = 1), where VSC has also power generation capability. The power rating of the converters and the appropriate proportion of the voltages between the converters was also allocated.
- A parallel hybrid converter composed from parallel connection of one VSC and one LCC converter was proposed, designed and simulated. It is shown that this converter is capable of operating into an electric system with very short circuit ratio (SCR = 1), where VSC has also power generation capability. The power rating of the converters and the appropriate proportion of the currents between the converters was also allocated.

- It is shown that both of the hybrid converter options provide higher commutation failure immunity index (CFII) compared to LCC-only converters. To have identical CFII, the LCC-only option needs to have considerably higher SCR.
- Technical feasibility of the SHC converters is demonstrated. It is concluded that the SHC option is a promising solution for feeding high power to very weak ac electric systems.
- Intrinsic drawback of the PHC converters is demonstrated. It is concluded that the PHC option is not a good candidate to work under very weak ac system conditions. This is because of its poor dynamic performance and its intrinsic drawback of responding to a group of faults.

5.6 Further recommendations for future work

The main concern of this study is demonstrating the feasibility of series and parallel hybrid converters. As a direct result of this, the controller parameters in simulated system have not been optimized in a global sense. Based on the results obtained, the following directions are proposed:

- Major tasks:
    - Using Manitoba HVdc system data to fully investigate the chance of substituting one of the conventional converter-based bi-poles with a VSC based inverter (PHC option)
    - Deriving a small signal model for SHC, and PHC hybrid options. This lets finer tuning of the controller parameters
    - Assessing the feasibility of connecting SHC and PHC hybrid converters to a dead system

  - Analyzing a multi-terminal HVdc system, based on a hybrid HVdc system in parallel with a LCC-only based system
- Minor tasks:
  - Performing an economical assessment of the hybrid converter
  - Optimizing the VSC’s dc capacitor size

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Appendix A: Hybrid Electrical System Design

A.1 Introduction

Allocating the appropriate voltage rating between VSC and LCC converter in series hybrid converter and current in parallel hybrid converter topology starts with the proposed optimization method (Section 3.6). The next step is obtaining the appropriate required reactive power generation from harmonic filters. This selection has been accomplished through an iterative method, based on a trade-off between minimum reactive power needed, and the rating attained based on harmonic analysis at ac inverter terminal (Section 3.6).

In the following sections, the transformer power rating for the hybrid options on inverter side is calculated. The rectifier rating is as per Cigré model, given in Table C.4. Finally the transformer voltages for the inverter side (hybrid options), and for the rectifier side is calculated.

A.2 Determining transformer power rating for the hybrid options

Using an iterative approach, the needed reactive power for stable operation of the SHC hybrid inverter is found to be equal to 103 Mvar. A similar procedure results in 110 Mvar for the reactive power needs of the PHC option. Based on optimization concept explained in section 3.6, the transformer ratings are calculated as follows. In the following calculations, 100 Mvar is used for the SHC option.

Using $Q_f = 100 M\text{var}$, assume that P_{LCC} represents the active LCC power and $0.6 * P_{LCC}$ expresses the LCC reactive power. At the VSC converter, the active and reactive power are, respectively:

$P_{VSC} = 1000 - P_{LCC}$, and $Q_{VSC} = 0.6 * P_{LCC} - Q_f$. So the parametric form for the apparent power at VSC, is:

$$S_{VSC} = \sqrt{P_{VSC}^2 + Q_{VSC}^2} = \sqrt{(1000 - P_{LCC})^2 + (0.6 * P_{LCC} - 100)^2} \qquad \text{(A-1)}$$

Taking the derivative of this equation and putting that equal to zero, leads to the following VSC ratings:

$$P_{VSC} = 220 \text{ MW} \;,\; Q_{VSC} = 370 \text{ Mvar} \;,\; S_{VSC} = 428 \text{ MVA} \qquad \text{(A-2)}$$

Then the total LCC rating is:

$$P_{LCC} = 784 \text{ MW} \;,\; Q_{LCC} = 470 \text{ Mvar} \;,\; S_{LCC} = 914 \text{ MVA} \qquad \text{(A-3)}$$

Here the conventional assumption of equal rating for each of the two LCC-inverter converters is used. These optimized values for converter transformer ratings have been implemented in simulating model for the SHC and PHC hybrid inverters.

A.3 Determining transformer rating for rectifier converter

Using 500 kV as the voltage on dc side of inverter and nominal current of the HVdc system, which is $I_{dc} = \frac{P_{dc}}{V_{dc}} = \frac{1000}{500} = 2 \text{ kA}$, the rectifier side parameters may be calculated based on dc line parameters:

$$V_{dc,\mathrm{Rec}} = 500 + R * I_{dc} = 510 \text{ kV} \qquad \text{(A-4)}$$

Using the basic relation between dc voltage and the fundamental voltage component of ac side of rectifier,

$$V_{dc,\mathrm{Re}\,c} = 1.35.n.V_{ac,\mathrm{Re}\,c} * \cos(\alpha) - \frac{3}{\pi}.X_C.n^2.I_{dc} \tag{A-5}$$

where α is the rectifier angle, n is the transformer ratio, $V_{ac,\mathrm{Re}\,c}$ is line-to-line voltage at rectifier's terminal (230 kV), I_{dc} is the direct current, and X_L is transformers leakage reactance (0.18 p.u.), or:

$$X_L = \frac{230^2}{1190} * 0.18 = 8\ \Omega \tag{A-6}$$

Now,

$$510 = 1.34.n.230.\cos(15) - \frac{3}{\pi}.8.n^2.2 \tag{A-7}$$

which leads to $n = 1.86$. So the secondary voltage of the VSC transformer is:

$$V_{\sec} = 230 * 1.86 = 420.1\ \mathrm{kV} \tag{A-8}$$

The transformer rating for the rectifier side is:

$$P_{\mathrm{Re}\,c} = 1000 + 20 = 1020\ \mathrm{MW}\,,\ Q_{\mathrm{Re}\,c} \approx 0.6 * 1020 = 612\ \mathrm{Mvar} \tag{A-9}$$

which leads to $S_{rec} = 1190\ \mathrm{MVA}$

A.4 Voltage and current calculations for hybrid options

A.4.1 Series hybrid converter

Using 500 KV as the inverter-side dc voltage (V_{Inv}), and using the P_{VSC} as in (A-5),

$$V_{VSC} = \frac{P_{VSC}}{2} = \frac{220}{2} = 110\ \mathrm{kV} \tag{A-10}$$

Based on this number, the LCC-inverter voltage is: $V_{LCC} = 390\ \mathrm{kV}$

Based on $S_{LCC} = 910\,\text{MVA}$, or 455 MVA for each of the LCC converter transformers in the inverter side, and assumption of 230 kV rms voltage for inverter terminal voltage at the system side of the transformer, its reactance would be equal to:

$$X_{LCC} = \frac{230^2}{910} * 0.18 = 10.464\ \Omega \tag{A-11}$$

To calculate the transformer rating for inverter LCC, we have:

$$V_{dc} = 1.35.n.230.\cos(\gamma) - \frac{3}{\pi}.X_L.n^2 * I_{dc} \tag{A-12}$$

or,

$$\frac{390}{2} = 1.35.n.230.\cos(15 * \frac{\pi}{180}) - \frac{3*2}{\pi} * 10.464 * n^2 * 2 \tag{A-13}$$

which leads to the transformer ratio of: $n = 0.722$, or accordingly:

$$V_{prim} = 230 * 0.722 = 166.06\ \text{kV} \tag{A-14}$$

In normal working conditions, the inverter works in voltage control mode, demanding some adjustments to be made on the calculated primary (inverter) side of the LCC converter. The adjusted voltage used in simulation is 169 kV.

Using the $V_{VSC} = 110\ \text{KV}$, the transformer voltage rating for VSC may be calculated. Assuming a modulation index (m) of $m = 0.8$, the fundamental frequency magnitude of voltage at ac side of VSC converter equals:

$$V_L = \frac{V_{dc}}{2} * m * \sqrt{\frac{3}{2}} \quad \text{or}:\ V_L = \frac{110}{2} * 0.80 * \sqrt{1.5} = 53.9\,\text{kV} \tag{A-15}$$

Based on the original design assumption of 1 p.u. (230 kV) voltage at ac inverter terminal voltage, the reactive power flow at terminal should be zero. In PSCAD simulation, the inverter side of VSC transformer has a high harmonic content, suggesting that the inverter side ac voltage would be lower than the design value, which will demand higher modulation index, which matches with steady state observations. Using real power rating for VSC of:

$$P_{VSC} = 110 * 2 = 220 \text{ MW} \tag{A-16}$$

and reactive power rating of:

$$\mathrm{Q_{VSC}} = 0.6 * 780 - 100 = 370 \text{ Mvar} \tag{A-17}$$

the final rating equals $S_{VSC} = 420 \text{ MVA}$.

A.4.2 Parallel hybrid converter

Using 500 KV as the inverter-side dc voltage (V_{Inv}), then $V_{VSC} = V_{LCC} = 500 \text{ kV}$. Based on total LCC power of $S_{LCC} = 910\,\text{MVA}$ (or 455 MVA for each of the LCC-converter transformers in the inverter side), and assuming the 230 kV rms voltage for inverter terminal voltage at the system side of the transformer, its reactance is:

$$X_{LCC} = \frac{230^2}{910} * 0.18 = 10.464\ \Omega \tag{A-18}$$

To calculate the transformer rating for inverter LCC,

$$V_{dc} = 1.35.n.230.\cos(\gamma) - \frac{3}{\pi}.X_L.n^2 * I_{dc} \tag{A-19}$$

or,

$$\frac{500}{2} = 1.35.n.230.\cos(15 * \frac{\pi}{180}) - \frac{3*2}{\pi} * 10.464 * n^2 * 2 \tag{A-20}$$

which leads to the transformer ratio of: $n = 0.722$, or accordingly:

$$V_{prim} = 230 * 0.722 = 166.06 \text{ kV} \tag{A-21}$$

In normal working conditions, the inverter works in current control mode, demanding some adjustments to be made on the calculated primary (inverter) side of the LCC converter. The adjusted voltage is 219 kV.

Using the $V_{VSC} = 500 \text{ kV}$, the transformer voltage rating for VSC may be calculated. Assuming a modulation index (m) of $m = 0.8$, the fundamental frequency magnitude of voltage at AC side of VSC converter will be equal to:

$$V_{ac,VSC} = \frac{V_{dc}}{2} * m * \sqrt{\frac{3}{2}} \quad \text{or}: V_{ac,VSC} = \frac{108}{2} * 0.80 * \sqrt{1.5} = 245 \text{kV} \qquad \text{(A-22)}$$

Using real and reactive part for converter,

$$P_{VSC} = 110 * 2 = 220 \text{ MW} \qquad \text{(A-23)}$$

Using the VSC reactive power of

$$\mathrm{Q}_{\mathrm{VSC}} = 0.6 * 780 - 100 = 370 \text{ Mvar} \qquad \text{(A-24)}$$

Leads to total VSC converter power of $S_{VSC} = 420 \text{ MVA}$.

Appendix B: Ac Filters

The filters size and their quality are two basic concepts in filter design. The size of the filter is defined as the reactive power that the filter supplies at fundamental frequency. The quality of the filter is a measure of its sharpness of tuning.

In the ac-filters used at the hybrid inverter designs, only single-tuned filters of 11, 13, 23, 25, 25, 29th order are used to target the lower order harmonics. Another single-tuned filter at 55th order (related to higher sideband of VSC's switching frequency). Here, the magnitude of filter impedances for both hybrid designs is plotted in Figure B.1. In this figure, $\left|Z_{fs}(\omega)\right|$ and $\left|Z_{fp}(\omega)\right|$, refer to magnitude of filter impedance for series, and parallel options, respectively.

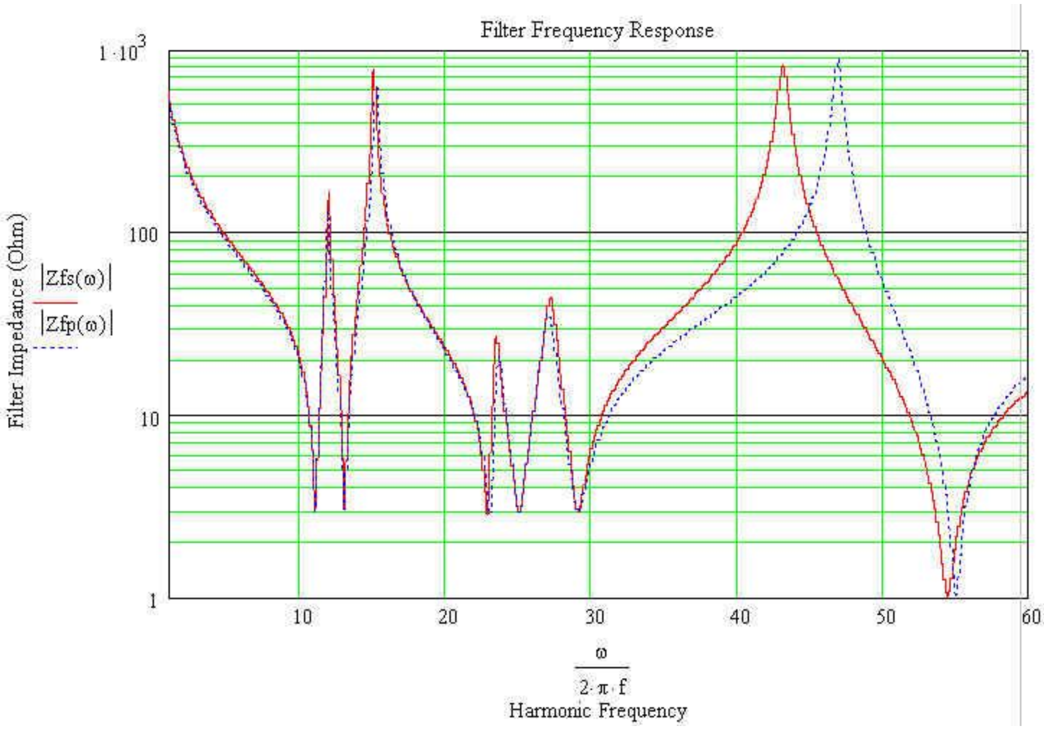

Figure B-1 Filter frequency response for the SHC / PHC hybrid options

In Figure B.2 the normalized frequency response for both designed filters have been plotted. Here $\frac{|Z_{fs}(\omega)|}{|Z_{sys}(\omega)|}$ and $\frac{|Z_{fp}(\omega)|}{|Z_{sys}(\omega)|}$ refer to the normalized hybrid option impedances versus system harmonic frequency.

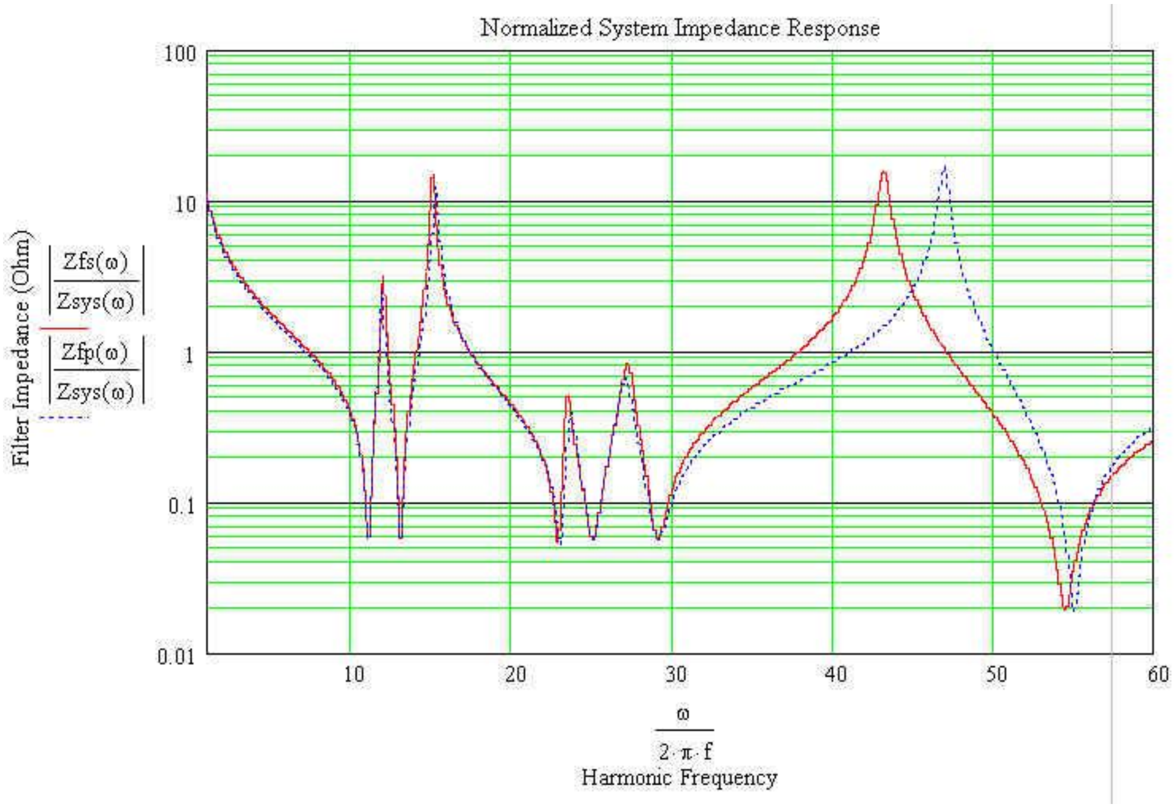

Figure B-2 Normalized filter frequency response for the SHC/PHC hybrid options

In Table B-1, the filter orders, along with inductor, capacitor and resistor magnitudes used in simulation cases are tabulated for both of the SHC and PHC options.

In Table B-2, the relative harmonic strength (D_i) for the individual frequencies, which have dedicated installed filters, have been given for both of the hybrid options.

Table B-1 Filter electric component values

Filter order	SHC filter components			SHC (Mvar)	PHC filter components			PHC (Mvar)
	L (mH)	C (μF)	R (Ω)		L (mH)	C (μF)	R (Ω)	
11 f_0	38.77	1.5	3	30	38.77	1.5	3	30
13 f_0	52.04	0.8	3	16	41.516	1.0028	3	20
23 f_0	27	0.5	3	10	22.92	0.5804	3	11.5
25 f_0	11.23	1.0028	3	20	11.23	1.0028	3	10
29 f_0	10.458	0.8	3	16	8.366	1	3	20
55 f_0	4.125	0.576	1	11.5	6.204	0.375	1	7.5

Table B-2 Relative voltage harmonic strengths at individual frequencies

Harmonic Component (%)	D_i content for SHC (%)	D_i content for PHC (%)
11th	0.24	0.25
13th	0.15	0.18
23rd	0.1	0.08
25th	0.21	0.23
29th	0.24	0.24
35th	0.13	0.12
37th	0.14	0.22
53rd	0.38	0.23
55th	0.19	0.18

Appendix C: Electrical and Controller Parameters

C.1 Ac system equivalent impedance

At the inverter (hybrid) side, the SCR = 1 and a system impedance damping angle of 75° is assumed. Based on the selected impedance, the ac system equivalent impedance used in PSCAD /EMTDC simulation is given in Table C-1.

Table C-1 Ac system equivalent impedance parameters

Resistance (Ω)	Inductance (H)
13.6915	0.13554

C.2 VDCOL characteristics

The optimization-based parameters used in simulation studies for SHC and PHC options are shown in Table C-2.

Table C-2 LCC inverter VDCOL characteristics used for hybrid options

Hybrid option	$V_{\mathrm{Re}\,c}$ (p.u.)	Current order (p.u.)
Series	≤ 0.3	0.3
	≥ 0.8	1
Parallel	≤ 0.5	0.15
	≥ 0.9	1.2

C.3 System and electrical parameters

In Table C-3, system-related and electrical transformer parameters for both of the hybrid options and the First Cigré Benchmark model are given.

Table C-3 Electrical system parameters for hybrid options used in simulation

Electrical system parameters for hybrid SHC and PHC options				
System ratings	Power	Ac voltage	Dc voltage	Dc current (I_{dc})
	1000 MW	230 kV, rms	500 kV	2 kA (1 p.u.)
SHC option	LCC converter		VSC converter	
	$V_{dc,LCC}$	$I_{dc,LCC}$	$V_{dc,VSC}$	$I_{dc,VSC}$
	390 kV	2 kA (1 p.u.)	110 kV	2 kA (1 p.u.)
PHC option	LCC converter		VSC converter	
	$V_{dc,LCC}$	$I_{dc,LCC}$	$V_{dc,VSC}$	$I_{dc,VSC}$
	500 kV	1.56 kA (0.78 p.u.)	500 kV	0.44 kA (0.22 p.u.)

Table C-4 System and transformer parameters for hybrid options used in simulation

Transformer ratings for hybrid SHC and PHC options						
Option	LCC inverter (each)		VSC		Rectifier	
	Power	Ratio	Power	Ratio	Power	Ratio
SHC	457 MVA	230/169 kV,LL	420 MVA	230/51 KV	603.7 MVA	345/213.46 kV,LL
PHC	458.3 MVA	230/219.4 kV	420 MVA	230/230 KV	603.7 MVA	345/213.46 kV,LL

C.4 SHC hybrid inverter and LCC rectifier control diagram

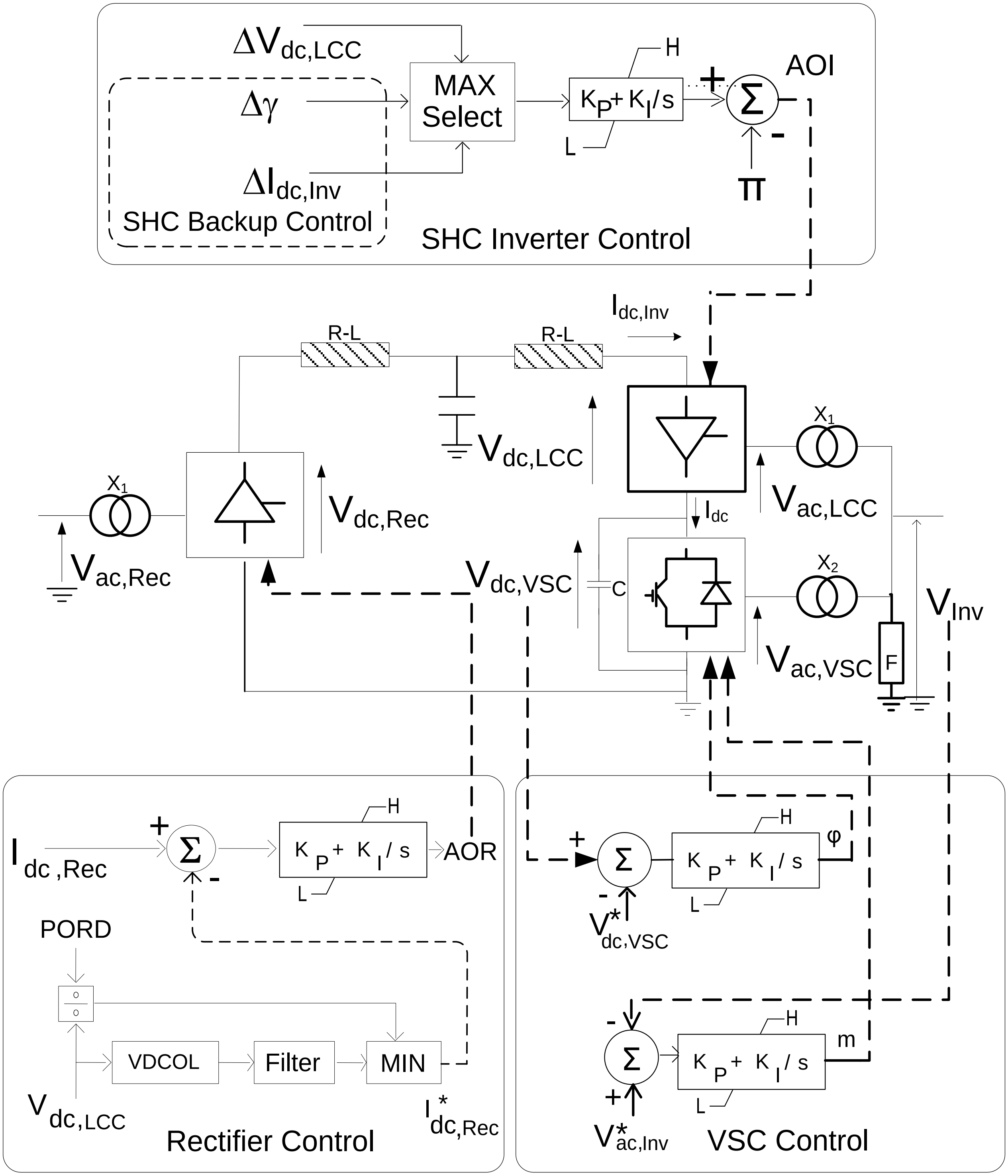

Figure C-1 SHC hybrid inverter and LCC rectifier control diagram

C.5 The SHC converter parameters

Table C-5 presents the controller gains for LCC inverter controllers, along with VSC control settings for the SHC option. In this table, K and T refer to gain and time constant for PI controllers, respectively. Also ϕ and m controllers, refer to PI controllers that generate the phase angle and modulation index signals that are input parameter to IGBT components.

Table C-5 Control settings for the SHC hybrid option

(a) The LCC converters

	LCC Rectifier	LCC (Inverter side)		
Parameter		Current controller	Gamma controller	Voltage controller
K	0.5	0.55	0.6	1.05
T	0.05	0.05	0.05	0.02
Low limit	0.0873	0.262	0.262	0.262
High limit	1.6	1	1.57	1.57

(b) The VSC converter

	VSC (Inverter side)		
Parameter	ϕ controller	m controller	Power controller
K	60	1.3	0.7
T	0.05	0.007	0.8
Low limit	-10 °	0.1	-0.02
High limit	90 °	1.2	0.02

C.6 PHC hybrid inverter and LCC rectifier control diagram

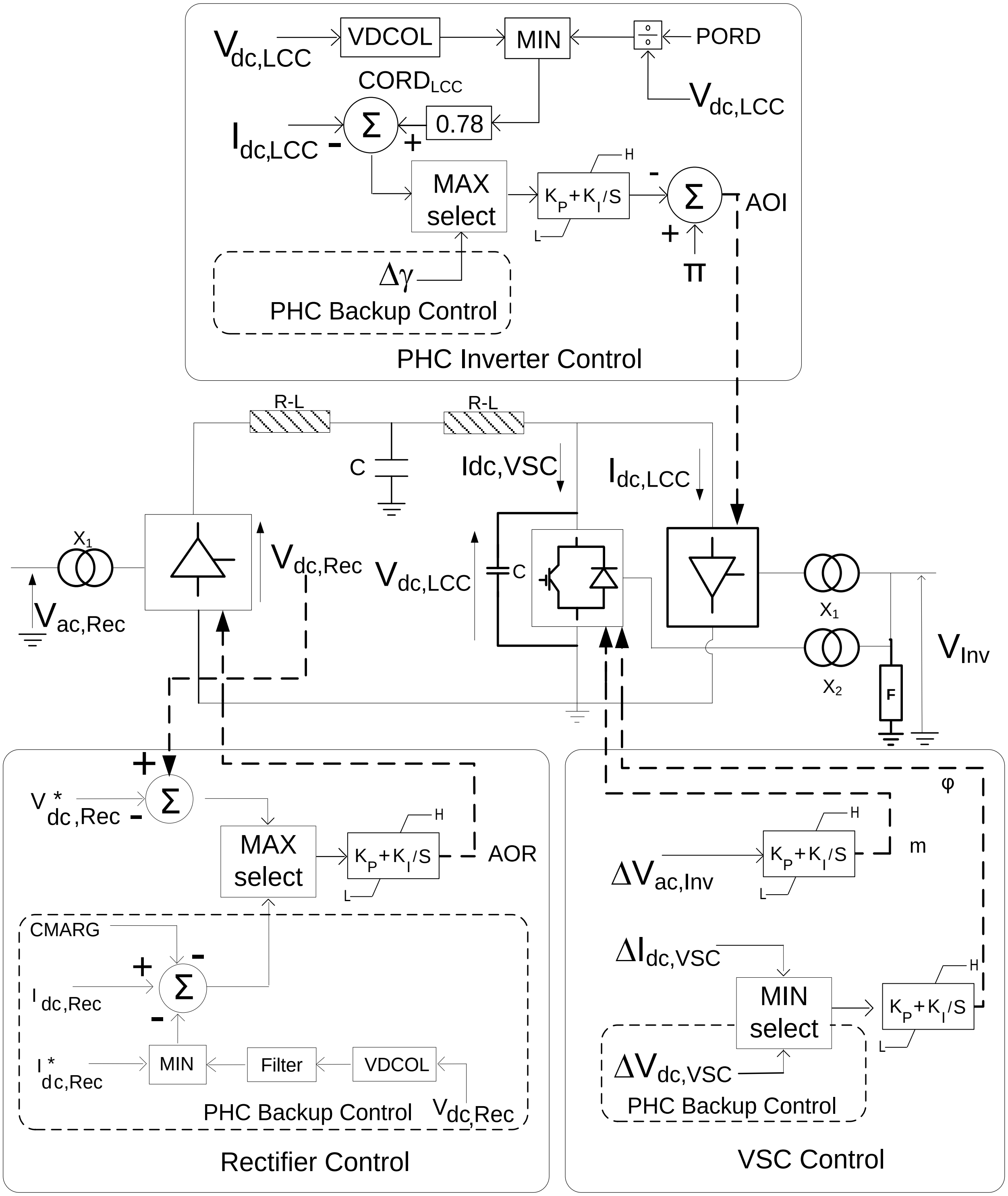

Figure C-2 PHC hybrid inverter and LCC rectifier control diagram

C.7 The PHC converter parameters

Table C-6 presents the controller gains for LCC inverter controllers, along with VSC control settings for the PHC option. In this table, K and T refer to gain and time constant for PI controllers, respectively. Also ϕ and m controllers, refer to PI controllers that generate the phase angle and modulation index signals that are input parameter to IGBT components.

Table C-6 Control settings for the PHC hybrid option

(a) The LCC converters

	LCC Rectifier		LCC (Inverter side)	
Parameter	Current controller	Voltage controller	Current controller	Gamma controller
K	0.6	1.02	0.98	0.23
T	0.03	0.08	0.19	0.11
Low limit	0.1	0.0873	0.262	0.262
High limit	1.65	1.57	1.6	1.6

(b) The VSC converter

	VSC (Inverter side)			
	ϕ controller		m controller	Power controller
Parameter	Current controller	Voltage controller		
K	10	50	2	0.7
T	0.02	0.01	0.1	0.8
Low limit	0 °	-15°	0.05	0.02
High limit	10 °	7°	1.2	-0.02

Appendix D: PSCAD Electrical System Map

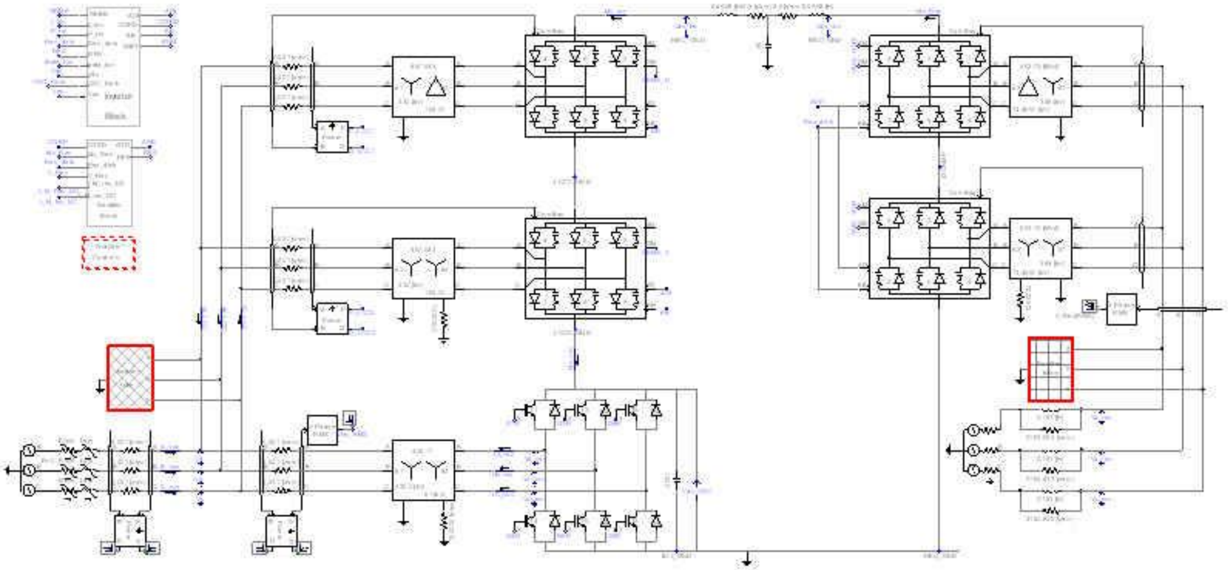

Figure D-1 PSCAD electrical layout for the SHC option

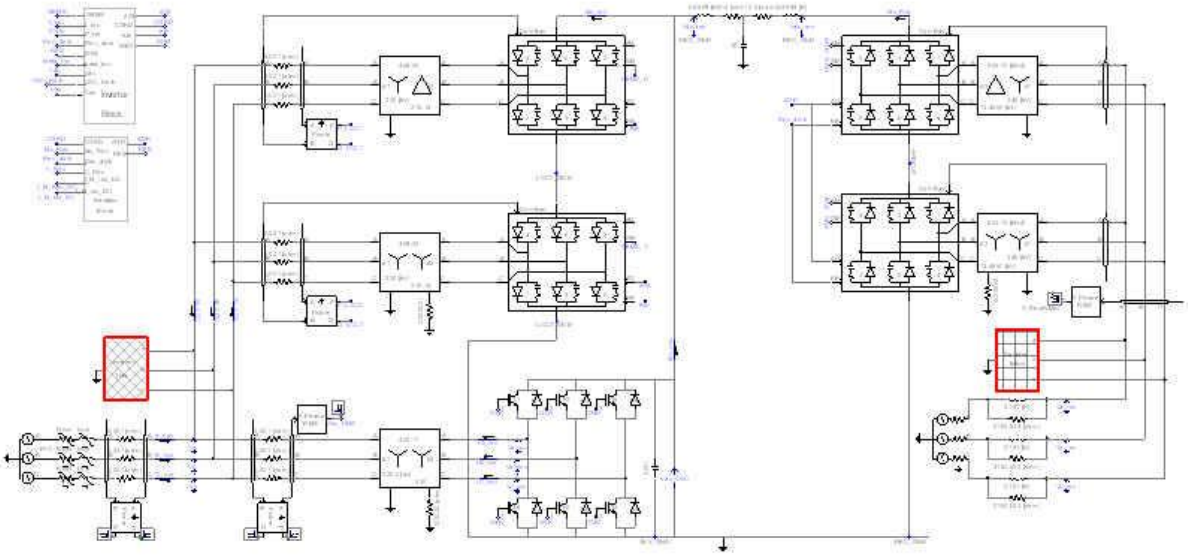

Figure D-2 PSCAD electrical layout for the PHC option

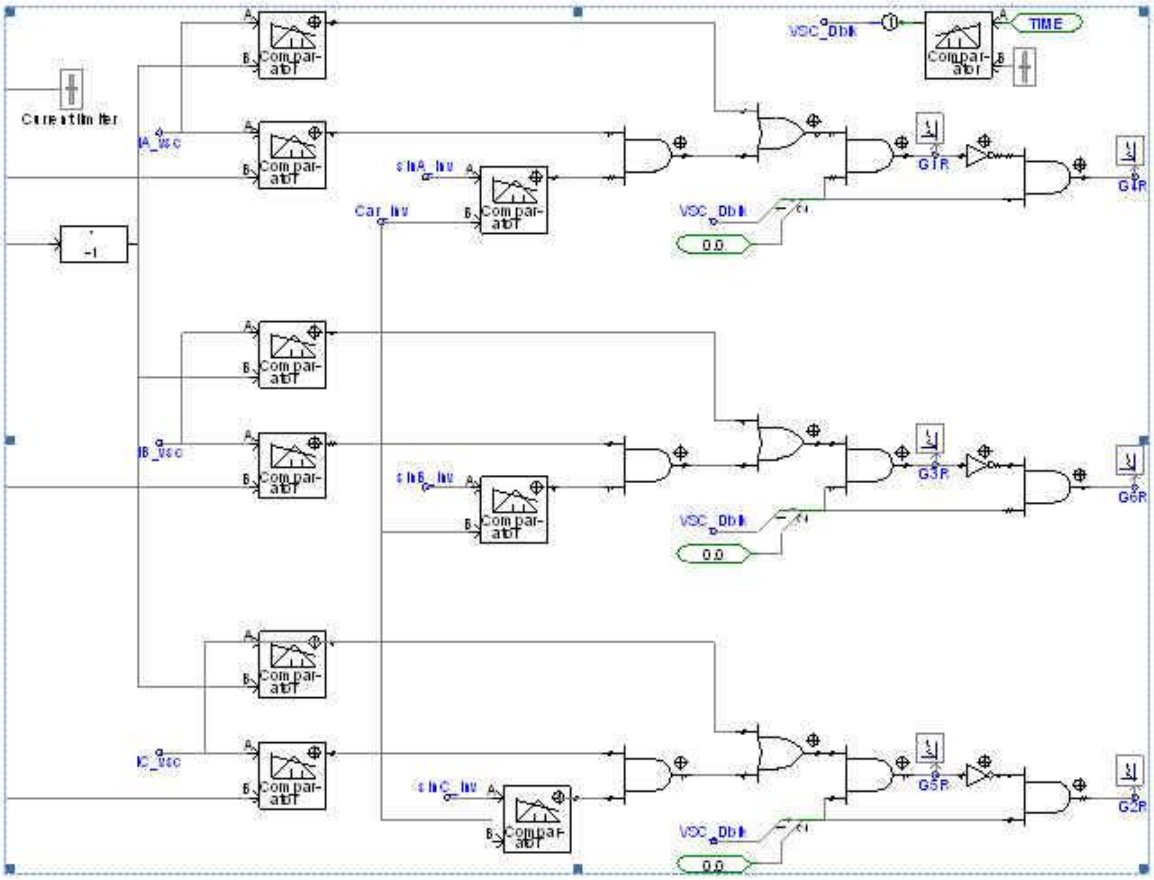

Figure D-3 PSCAD control logic diagram for IGBT overcurrent control