A project report on

"Control of Power Flow with the Use of Distributed Power Flow Controller (DPFC)"

A dissertation submitted in partial fulfillment of the requirement for the award of the degree of

MASTER OF TECHNOLOGY

IN

POWER SYSTEM

By

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CERTIFICATE

This is to certify that this dissertation entitled ***"Control of Power Flow with the Use of Distributed Power Flow Controller (DPFC)"*** is an authentic report of the project done by ***MANISH SHAKYA*** in the partial fulfillment of the requirement for the award of the degree of **Master of Technology** in **Power systems** by the Delhi Technological University during the year, 2012-13.

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ACKNOWLEDGEMENT

I take this opportunity to express my sincere gratitude to all those who have been instrumental in the successful completion of this project.

First and foremost, I express my sense of gratitude to my guide **Mrs. PRIYA MAHAJAN**, Assistant Professor, Department of Electrical Engineering, Delhi Technological University for her constant supervision and valuable suggestions for my thesis work entitled ***"Control of Power Flow with the Use of Distributed Power Flow Controller (DPFC)"***. This project would not have been possible without her help and the valuable time that she has given me amidst of her busy schedule.

I wish to take this opportunity to express my gratitude to **Prof. Madhusudan Singh**, Head of Department and **Prof. Narendra Kumar**, Ex-Head of Department of Electrical Engineering Department for their constant encouragement during the conduct of the project work.

I would like to thank **Dr. Rachana Garg** and **Dr. Suman Bhaumick**, Department of Electrical Engineering, Delhi Technological University for helping me in my tuff times during the completion of this thesis and all those who have directly and indirectly helped me in completion of thesis well in time.

I would also like to extend my gratitude to my younger brother **Shri. Avneesh Shakya**, Technical Officer, Department of Atomic Energy, ECIL, Hyderabad (India) and all my batch mates who have always encouraged and supported me in doing my work.

With great pleasure and respect, I express my utmost gratitude to my beloved **parents, my family members** for their moral support and confidence showed in me to pursue M.Tech at advanced stage of my academic career.

Last but not the least I would like to thank all the staff members of Department of Electrical Engineering who have been very cooperative with us.

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ABSTRACT

In modern power systems, there is a great demand to control the power flow actively. Power flow controlling devices (PFCDs) are required for such purpose, because the power flow over the lines is depends on the nature of the impedance of the each line. Due to the control capabilities of different types (of PFCDs, the trend is that mechanical PFCDs are gradually being replaced by Power Electronics (PE) PFCDs. Among all Power Electronic PFCDs, the Unified Power Flow Controller (UPFC) is the most versatile device. However, the UPFC is not widely applied in utility grids, because the cost of such device is much higher than the rest of PFCDs and the reliability is relatively low due to its complexity.

The objective of this project is to present a new PFCD that offers the same control capability as the UPFC, at a reduced cost and with an increased reliability. The new device, so-called Distributed Power Flow Controller (DPFC), is introduced and presented in this project. The DPFC is a further development of the UPFC. The DPFC provides comparable performance as the combined FACTS device - the UPFC, acceptable cost to electric utilities and reliability for power systems. The DPFC eliminates the common DC link within the UPFC, to enable the independent operation of the shunt and the series converter. The D-FACTS concept is employed in the design of the series converter. Multiple low-rating single-phase converters replace the high-rating three-phase series converter, which greatly reduces the cost and increases the reliability. The active power that used to exchange through the common DC link in the UPFC, is now transferred through the transmission line at the 3rd harmonic frequency.

This project starts with the review the state-of-art of current PFCDs, followed by the research at the DPFC device level, including the operation principle, the modeling and control, and experimental demonstrations and the feasibility of the DPFC for real networks. The DPFC has been modeled in a rotating dq-frame. Based on this model, the basic control of the DPFC is developed. The basic control stabilizes the level of the capacitor DC voltage of each converter and ensures that the converters inject the voltages into the network according to the command from the central control. The shunt converter injects a constant current at the 3rd harmonic frequency, while its DC voltage is stabilized by the fundamental frequency component. For the series converter, the reference of the output voltage at the fundamental frequency is obtained from the central controller and the DC voltage level is maintained by the 3rd harmonic component.

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LIST OF ABBREVIATIONS

DPFC	Distributed Power Flow Controller
IPFC	Interline Power Flow Controller
UPFC	Unified Power Flow Controller
TCSC	Thyristor Controlled Series Compensators
TSSC	Thyristor Switched Series Capacitor
DSSC	Distributed Static Series Compensator
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator devices
TSC	Thyristor-Switched Capacitors
TCR	Thyristor-Controlled Reactor
SVC	Static Var Compensator
DVR	Dynamic Voltage Restorer
DSC	Distribution Series Capacitors
PST	Phase Shifting Transformer
IMC	Internal Model Control
PLL	Phase-Lock-Loop
MOSFET	Metal Oxide Semiconductor Field Effect Transistors
HVDC	High Voltage Direct Current
PFCD	Power Flow Controlling Device
APF	Active Power Filters
FACTS	Flexible AC Transmission Systems
GTO	Gate Turn-Off thyristors
PWM	Pulse-Width Modulated

S_r	Apparent power
P_r	Active power
Q_r	Reactive power
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistors
IPAC	In-phase Advanced Compensation
kV	Kilo volt
ms	Milli second
MVA	Megavolt ampere
MVAR	Mega volt amps reactive
MW	Megawatt
p.u.	Per unit
PCC	Point of common coupling
RMS	Root mean square
VSC	Voltage Source Converter
IDVR	Interline dynamic voltage restorer
mH	Milli Henery

Chapter-1

1.1 INTRODUCTION

The electrical power system serves to deliver electrical energy to consumers. An electrical power system deals with electrical generation, transmission, distribution and consumption. In a traditional power system, the electrical energy is generated by centralized power plants and flows to customers via the transmission and distribution network. The rate of the transported electrical energy within the lines of the power system is referred to as 'Power Flow' to be more specific; it is the reactive power and active that flows in the transmission lines [1, 2].

During the last two decades, operation of power systems has changed due to growing consumption, the development of new technology, the behavior of the electricity market and the development of renewable energies. In addition to existing changes, in the future, new devices, such as electrical machines, distributed generation and smart grid concepts, will be employed in the power system, making the system extremely complex.

1.2 POWER FLOW CONTROLLING DEVICES

By adjusting the parameters, Power flow is controlled of a system, for example voltage magnitude, transmission angle and line impedance. The device that attempts to vary system parameters to control the power flow can be described as a Power Flow Controlling Device (PFCD).Depending on how devices are connected in systems, PFCDs can be divided into shunt devices, series devices, and combined devices (both in shunt and series with the system), as shown in Figure 1-2.

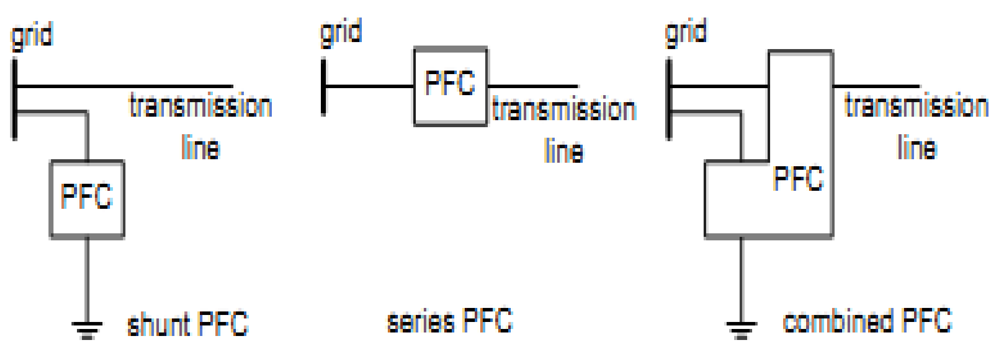


Figure 1-1: diagram of shunt, series and combined devices [1]

A shunt device is a device that connects between the grid and the ground. Shunt devices generate or absorb reactive power at the point of connection thereby controlling the voltage magnitude. Because the bus voltage magnitude can only be varied within certain limits, controlling the power flow in this way is limited and shunt devices mainly serve other purposes.

For example, the voltage support provided by a shunt device at the middle of transmission line can boost the power transmission capacity.

A combined device is a two-port device that is connected to the grid, both as a shunt and in a series, to enable active power exchange between the shunt/series parts. Combined devices are suitable for power flow control because they can simultaneously vary multiple system parameters, such as the transmission angle, the bus voltage magnitude and the line impedance. Based on the implemented technology, PFCDs can be categorized into mechanical based devices and power electronics (PE)-based devices [2, 3]

Another application of shunt devices is to provide reactive power locally, thereby reducing unwanted reactive power flow through the line and reducing network losses. Also, consumer-side shunt devices can improve power quality, especially during large demand fluctuations. The operating principle of shunt devices can be found in chapter-2. A device that is connected in series with the transmission line is referred to as a ‘series device’. Series devices influence the impedance of transmission lines. The principle is to change (reduce or increase) the line impedance by inserting a reactor or capacitor. To compensate for the inductive voltage drop, a capacitor can be inserted in the line to reduce the line impedance. By increasing the inductive impedance of the line, series devices are also used to limit the current flowing through certain lines to prevent overheating [19].

Mechanical PFCDs consist of fixed or mechanical interchangeable passive components, such as inductors or capacitors, together with transformers. Typically, mechanical PFCDs have relatively low cost and high reliability. However, because of their relatively low switching speed (from several seconds to minutes) and step-wise adjustments of mechanical PFCDs, they have relatively poor control capability and are not suitable for complex networks of the future.

Power Electronic PFCDs also contain passive components, but include additional Power Electronic switches to achieve smaller steps and faster adjustments. There is another term – Flexible AC Transmission System (FACTS) - that overlaps with the Power Electronic Controlling Devices. Normally, the High Voltage DC transmission (HVDC) and Power Electronic devices that are applied at the distribution network, such as a Dynamic Voltage Restorer (DVR), are also considered as FACTS controllers. Most of the FACTS controllers can be used for power flow control. However, the HVDC and the DVR are out of the scope of the PFCD [1]. The relationship between the PFCDs, FACTS controllers and mechanical controller is shown in Figure 1-2.

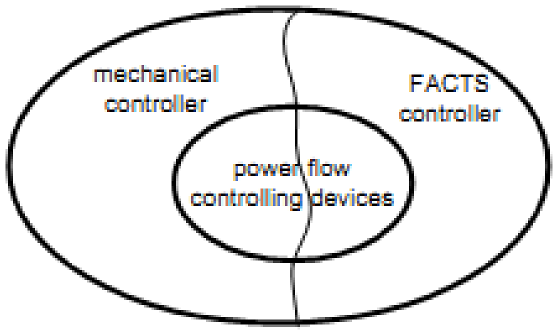


Figure 1-2: Relationship between the PFCDs, FACTS controllers and mechanical controller

Power Electronic PFCD devices can be further subcategorized into two types according to the applied switch technologies: thyristor-based devices and Voltage Source Converter (VSC) based devices. Thyristor PFCDs use inverse-parallel thyristors in series or in parallel with passive components. By controlling the firing angle of the thyristors, the impedance of the device can be adjusted. A thyristor can be controlled to turn on but not to turn off. It will turn off automatically when the current goes negative.

Consequently, the thyristor can only be turned on once within one cycle. The switching frequency of thyristor PFCDs is therefore limited to the system frequency (50/60 Hz), resulting in low switching losses. Because thyristors can handle larger voltages and currents than other power semiconductors, the power level of thyristor PFCDs are also higher. The thyristor PFCDs are simpler than VSC PFCDs, allowing them higher reliability. However, the waveforms of voltages and currents generated by thyristor PFCDs contain a large amount of harmonics, thereby requiring large filters.

VSC PFCDs employ advanced switch technologies, such as Insulated Gate Bipolar Transistors (IGBT), Insulated Gate Commutated Thyristors (IGCT), or Metal Oxide Semiconductor Field Effect Transistors (MOSFET) to build converters. Because these switches have turn-on and turn-off capability, the output voltage of a VSC is independent from the current. Consequently, it is possible to turn the switches on and off within the VSC multiple times within one cycle. Several types of VSCs have been developed, such as multi-pulse converters, multi-level converters, square-wave converters, etc.

These VSCs proved a free controllable voltage in both magnitude and phase. Due to their relatively high switching frequency, VSC PFCDs make practically instant control (less than one cycle) possible. High switching frequencies also reduce low frequency harmonics of the outputs and even enable PFCDs to compensate disturbances from networks. Therefore, VSC PFCDs are the most suitable devices for future power systems.

On the other hand, there are some challenges facing VSC PFCDs. Firstly, because large amounts of switches are connected in series or in parallel to allow the high voltage and high current through, the VSC PFCDs are expensive. In addition, due to their higher switching frequency and higher on-state voltage in comparison with thyristors.

VSC PFCD losses are higher as well. However, with developments in power electronics, VSC PFCDs can become more feasible and cost-effective in the future [1, 2].

According to the above considerations of different types of PFCDs, it can be concluded that Power Electronic combined PFCDs (also referred to as combined FACTS) have the best control capability among all PFCDs. They inherit the advantages of Power Electronic PFCDs and combined PFCDs, which is the fast adjustment of multiple system parameters. The Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) are currently the most powerful PFCDs; they can adjust all system parameters like transmission angle, line impedance and bus voltage. The operating principle of the UPFC and the IPFC will be discussed in further chapter [16].

1.3 MOTIVATION

Although the UPFC and the IPFC have superior capability to control power flow, there is no commercial application currently. The main reasons are:

• The first concern with combined FACTS is cost. Typically, a FACTS cost around 120-150 $ per kVA, compared to 15-20 $ per kVA for static capacitors. One of the reasons for the high cost is that the ratings of FACTS devices are normally in 100 MVA, with the system voltage from 100 kV to 500 kV. This requires a large number of power electronic switches in series and parallel connection. To provide voltage isolation, 3-phase high-voltage transformers are essential; furthermore, the series-connected transformers require an even higher rating to handle fault voltages and currents. Secondly, as the FACTS devices are installed at different locations for different purposes, each of them is unique. As a result, each FACTS device requires custom design and manufacturing, which leads to a long building cycle and high cost. Lastly, FACTS is a complex system, and requires a large area for installation and also well-trained engineers for maintenance.

• The second concern is possible failures in the combined FACTS. Two issues are considered: the reliability of the device itself and its influence on power system security. The combined FACTS is a complex system, which contains a large number of active and passive components. The large component number results that, without proper precautions, the combined FACTS have a bigger chance of failure than other PFCDs. To gain the desired reliability, complex protections (bypass circuit) and redundant backups (backup transformers and capacitor banks) are always provided for the combined FACTS device, further raising the cost, an already concerning factor. Also, a failure in the combined FACTS is more critical to the power system than in other devices. For a shunt FACTS, device failure results in a disconnection of the device from the grid which prevents it from providing reactive compensation. Because the series converter of the combined FACTS is directly inserted into transmission lines, not only the device, but also the transmission lines will be disengaged from the system during the failure.

Due to these two major drawbacks, the UPFC and IPFC are not widely applied in practice. Even when there is a large demand of power flow control within the network, the UPFC and IPFC are not currently the industry's first choice. Normally, a phase shifting transformer, which has less control capability, is selected for economic reasons. Accordingly, a low-cost, reliable combined FACTS device has great market potential.

First concern is the cost of the devices which will be used in the project it must be like that UPFC and IPFC but not exactly the same as the UPFC and IPFC because these devices having some drawbacks and high cost so I think to reduce the cost first. Country like INDIA cost is the great factor to implement any project to real time system. After that, we see the drawbacks of the UPFC and IPFC and try to reduce the same.

1.4 PROBLEMS & APPROACH OF THE TOPIC

There is a great demand of power flow control in power systems of the future and combined FACTS devices are the most suitable devices. However, due to the cost and the reliability issues given above, there are many hurdles to the widespread application of combined FACTS devices. Accordingly, the main objectives of this project can be summarized as:

For developing a new power flow controlling device that has given below characteristics:

• Comparable performance as the combined FACTS device - the UPFC or IPFC [2, 3].

• Acceptable cost to electric utilities.

• Acceptable reliability for power systems.

The approach to develop such a device consists of the following steps:

• Review the fundamentals of power-flow-control theory and the state-of-art of PFCDs with respect to operating principles, advantages and limitations.

• Analyze the UPFC and IPFC to determine their performance of power flow control.

• Find ways to reduce the cost and increase the reliability of combined FACTS devices.

• Generate a new concept of a power flow controlling device according to these points.

The new concept presented in this project is called 'Distributed Power Flow Controller (DPFC)'. It is a combined FACTS device, which has taken a UFPC as its starting point. The DPFC has the same control capability as the UPFC. The DPFC eliminates the common DC link that is used to connect the shunt and series converter back-to-back within the UPFC. By employing the Distributed FACTS concept as the series converter of the DPFC, the cost is greatly reduced due to the small rating of the components in the series converters. Also, the reliability of the DPFC is improved because of the redundancy provided by the multiple series converters [3, 4].

1.5 OUTLINE OF THESIS

The whole work of dissertation is organized in 6 chapters.

Chapter-1: Presents the general introduction of, transmission, distribution and consumption along with the problems related to transmission & voltage stability. Also we introduce the FACTS family elements and use of these with respect to transmission capability with motivation of project.

Chapter-2: Contains the literature review of the thesis and overview of the power flow controlling devices with working principles and related equations.

Chapter-3: Contains the introduction about Distributed Power Flow Controller (DPFC) like operating principle, DPFC control & control range, limitations etc.

Chapter-4: Contains the DPFC modeling and basic control.

Chapter-5: Contains the simulation results which elaborate in the chapter-4.

Chapter-6: Contains the thesis conclusion and future scope of the topic.

Chapter 2

LITERATURE REVIEW & OVERVIEW OF POWER FLOW CONTROLLING DEVICES

2.1 INTRODUCTION

It is shown in the previous chapter that there is a growing demand for fast, reliable and multi-directional power flow control. To achieve this, special devices are needed. This chapter gives an overview of the state-of-art of PFCDs, considering the operating principles and the advantages and limitations of each device. First the theory of power flow control is discussed and the parameters that can be used to control power flow are presented. Later, several PFCDs are categorized and introduced [1].

2.1.1 Literature review

Zhihui Yuan Sjoerd W.H. de Haan and Jan A. Ferreira [22] explained that he distributed Power Flow Controller (DPFC) is a new device that is a member of the FACTS family. DPFC can exercise control as the UPFC, but with high reliability and less cost. Observed in this work DPFC can independently control both type of powers like active & reactive power.

Z. Yuan, S.W.H. de Haan and JA Ferreira [26] have explained time and specifies the particular case whether series converter does not work. UPFC is DPFC generation device and has a relatively high reliability and lower cost. It was composed of two types of converters that are connected in series and a shunt network. The exchange of active power between the shunt and series converters is through the common DC link in the UPFC, is now that the transmission line at the third harmonic frequency. The redundancy of the series converters provide high system reliability. According to this document, it is considered DPFC behaviour during the failure of a single unit conversion series. The control principle is based on the fact that the failure of single serial converter will result in the asymmetric current at the fundamental frequency.

Zhihui Yuan, Sjoerd W. H. de Haan and Braham Ferreira as explained in [27] this work has been given information that the sustained stability when the controller shunt failure. DPFC reliability is given by the redundancy of multiple converters in series. The shunt converter is the bottleneck for the remaining reliability because there is only one converter bypass system DPFC. This paper presents a control DPFC, which keeps the system stable during DPFC parallel converter failure occurs. Adapted control schemes are used for each series converters, which can automatically change the drive mode series between total control and limited control mode.

P. Ramesh, Dr. M.damodara reddy [25, 27] these paper mainly focused on the steady state of the network. The review paper describes the steady-state response and control of power in the transmission line equipped with FACTS devices. Detailed simulations are performed in two machines systems to illustrate the control features of these devices and their influence to increase the power transfer capability and improved reliability. The DPFC is derived from the flow controller unified power flow controller (UPFC) and DPFC has the same capacity as the UPFC control. The DPFC can be considered a UPFC a common DC link removed. The exchange of active power between the shunt and series converters, which is through the common DC link in the UPFC, is now through the transmission lines at the 3rd harmonic frequency. The interaction between DPFC, the network and the machines are analyzed.

O.Sushma and Dr. K. S. R. Anjaneyulu [21] have explained that the DPFC employs distributed FACTS (D-FACTS) concept, which is the use of multiple phase converters small rather than large size phase converter in the UPFC series. The large number of series converters provide redundancy, increasing system reliability. As the D-facts are single phase and floating with respect to ground, there is required high voltage isolation between the phases. Accordingly, system cost is lower in DPFC than the UPFC. The DPFC has the same capacity as the UPFC control, comprising adjusting the impedance of the line, the angle of transmission, and bus voltage.

Ahmad Jamshidi, S. Masoud Barakati and Mohammad Moradi Ghahderijani [24] In this paper they have worked on improving power quality. According to the growth in electricity demand and the increasing number of non-linear loads in energy networks, providing a high quality electrical power must be considered. In this paper, voltage sag and swell of power quality problems are studied and flow controller distributed energy is used to mitigate the voltage deviation and improve power quality. The DPFC is a new FACTS device, its structure is similar to the unified power flow controller (UPFC). Although UPFC, in the dc-link DPFC common between the shunt and series converters is eliminated and the three-phase series converter is divided into several series-phase converters distributed through the line. The case study contains a DPFC located in a power system bus of infinite single machine, including two parallel transmission lines that simulated in MATLAB / Simulink environment.

2.2 POWER FLOW CONTROL THEORY

To study the power flow through a transmission line, a mathematical representation of a transmission line is required. A transmission line can be characterized by four parameters: resistance, inductance, capacitance and conductance. Conductance accounts for the leakage current at the insulators of overhead lines. However, for a short and medium length line (less than 240 km), the capacitance and conductance are so small that they can be neglected with little loss of accuracy. Accordingly, a transmission line can be Simplified as shown in Figure 2-1, where V_s and V_r are the sending and receiving end line-to-ground phasor voltages, ‘I’ is the phasor current through the line, and R and L are the series resistance and inductance of the line, respectively.

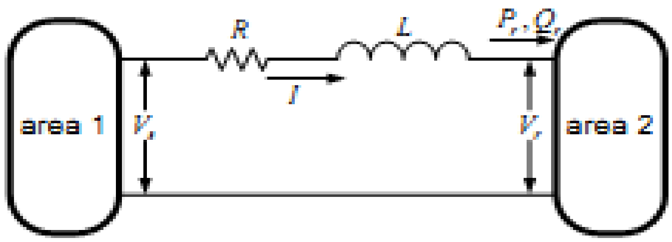


Figure 2-1: Simplified one-line representation of a transmission line

From the diagram, the power flow S_r through the line at the receiving end is given by:

$$S_r = V_r . I^* = \left(\frac{V_r - V_s}{R + j\omega L}\right)^* = P_r + jQ_r \qquad (2.1)$$

Where '∗' means the conjugation of a complex number, and ω is the angular frequency of the power system. The line impedance can be written as 'Z' and it is equal to R+jωL. The real part of S_r is the active power P_r and the imaginary part is the reactive power Q_r. According to (2.1), the active and reactive power flow at the receiving end are given by:

$$P_r = \frac{|V_r|^2}{|Z|}\cos\delta + \frac{|V_r||V_s|}{|Z|}\cos(\theta - \delta)$$

$$Q_r = \frac{|V_r|^2}{|Z|}\sin\delta + \frac{|V_r||V_s|}{|Z|}sin(\theta - \delta) \qquad (2.2)$$

where 'θ' is the angle between the sending and receiving ends' voltages, referred to as the transmission angle, and 'δ' is defined as tan−1(ωL/R). In a typical high-voltage or medium voltage transmission line, the reactance is normally much larger (over 10 times) than the resistance. Therefore, the resistance can be neglected during the power flow calculation with little loss of accuracy, and the active and reactive power flow through a lossless line can be Simplified to the following:

$$P_r = \frac{|V_r||V_s|}{|X|}\sin\theta$$

$$Q_r = \frac{|V_r||V_s|}{|X|}\cos\theta - \frac{|V_r|^2}{X} \qquad (2.3)$$

where X = ωL is the inductive impedance of the line. Equation (2.3) shows that three system parameters can by utilized to vary the power flow; transmission angle θ, line impedance X and bus voltage magnitudes $|V_r|$ and $|V_s|$. Because power systems are operated in a unified voltage mode (voltages are close to 1 per unit (pu), power flows can only be adjusted in a small range by varying the bus voltage magnitude. Therefore, the bus voltage magnitude is not suitable for controlling the power flow over a large range. By assuming that the bus voltages at the sending and receiving ends have the same magnitude |V|, the power flow equations can be further Simplified to:

$$P_r = \frac{|V|^2}{X}\sin\theta$$

$$Q_r = \frac{|V|^2}{X}(1-\cos\theta) \qquad (2.4)$$

As shown, the active and reactive power flow are coupled. By varying one parameter, both active and reactive power flow will change accordingly. From (2.4), the locus of (P_r,Q_r) with 'X' and 'θ' as the control parameter is achieved and shown in Figure 2-2.

By adjusting the transmission angle, both the magnitude and direction of the active power flow can be controlled; but for the reactive power flow, only the magnitude, but not the direction can be controlled, as shown in Figure 2-2. The variation range of θ' is (−90◦, 90◦), because the trigonometric functions are periodic functions. The line impedance 'X' can be changed to inductive or capacitive (although the capacitive line impedance is not common). Accordingly, by varying X, the magnitude and the direction of both the active and reactive power flow can be widely controlled. Theoretically, both active and reactive power flow can be adjusted from zero to infinity by changing the line impedance [1, 2].

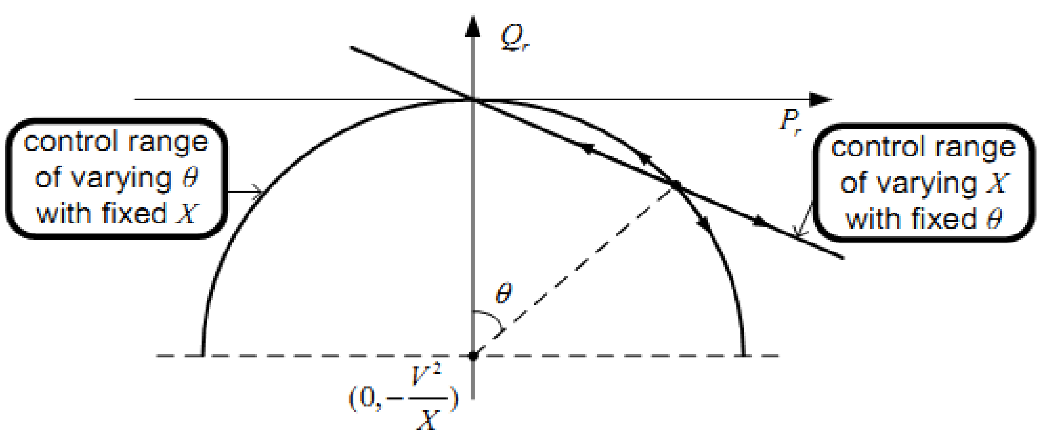


Figure 2-2: Control range of active and reactive power flows with vary θ and X [19]

By varying single parameter, there is only one degree of freedom for controlling the power flow. Normally the active power flow control has priority because the reactive power can be generated at the load side though capacitor banks. If the active and reactive power flows need to be controlled independently, two or more parameters should be simultaneously controlled by the PFCD [19].

2.3 CATEGORIZATION OF PFCDs

As has already been explained in chapter-1, the main categories of PFCDs are mechanical and power electronic-based regarding incorporated technology and shunt, series and combined devices based on their placement in the network. Figure 2-3 gives most of the important PFCDs and their categorization.

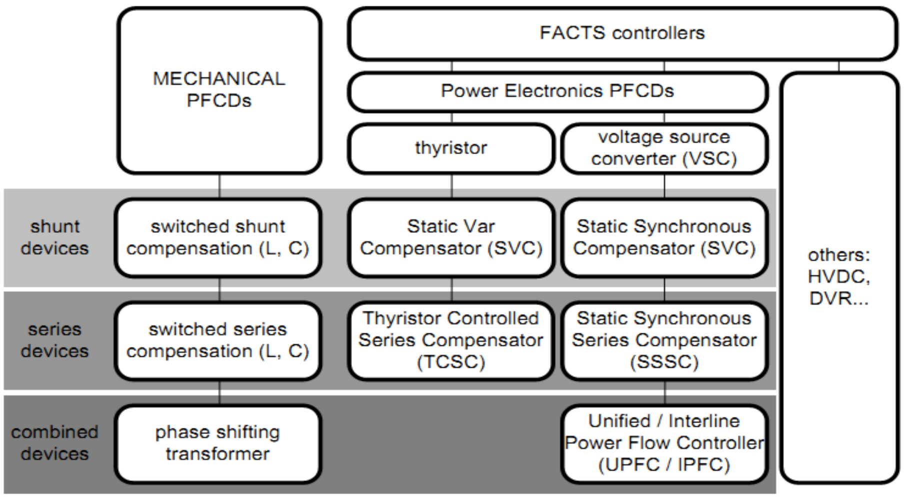


Figure 2-3: Categorization of PFCDs

2.4 SHUNT DEVICES

The basic principle of a shunt device is shown in Figure 2-4. The idea is to supply the reactive power locally that is required by the load. By varying the impedance of the shunt device, the injected reactive current I_{sh} can be adjusted, thereby indirectly controlling the line current 'I'. According to Ohm's law, the voltage drop across the transmission line $V_s - V_r$ is correlated to the line current 'I'. As the voltage at the sending end V_s can be assumed a constant value, the magnitude of the receiving end voltage $|V_r|$ can then be controlled by the shunt devices [1, 2].

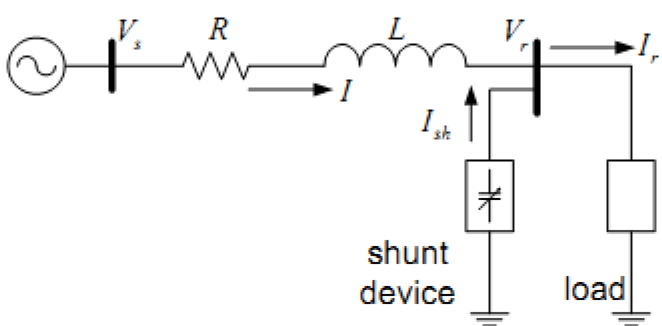


Figure 2-4: Shunt device operating principle

This indirect relationship between the current injected by the shunt device I_{sh} and the voltage V_r can be found in the following equation:

$$V_r = V_s - I_z = V_s - (I_r - I_{sh})Z \qquad (2.5)$$

where Z = R + jωL. As shown in (2.5), the shunt current I_{sh} can partly compensate for the large load current I_r, thereby reducing the line current 'I' in heavy load conditions and leading to a small voltage drop.

Accordingly, the shunt device can control the voltage magnitude by varying its impedance. Three types of shunt devices can be distinguished: switched shunt inductor and capacitor devices, Static Var Compensation (SVC) devices and Static Synchronous Compensator (STATCOM) devices. The configuration of the switched shunt inductor and capacitor device is shown in Figure 2-5. As the switched shunt inductor and capacitor device only has two statuses (on and off), its operation and principles are relatively simple and will not be discussed here. The SVC and STATCOM devices will be introduced in the following sections [2, 14].

2.4.1 SVC

A Static Var Compensator (SVC) is an electrical device used to provide fast acting reactive power on the transmission of high voltage electricity. It is a shunt-connected device whose output is adjusted to exchange inductive or capacitive current so as to control or maintain specific parameters of the electrical power system (typically bus voltage).

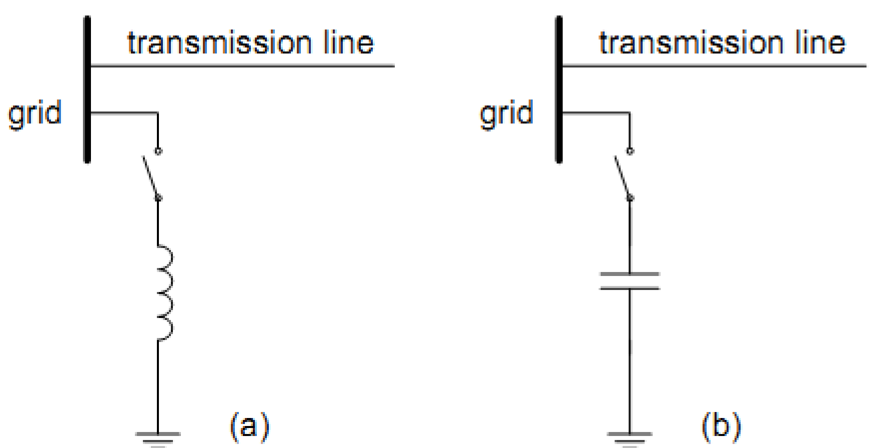


Figure 2-5: Switched shunt inductor and capacitor configuration: (a) inductor; (b) capacitor

The first commercial SVC was installed in 1972. Since then, it has been widely used and represents the most accepted FACTS device. Typically, a SVC is comprised of a bank of Thyristor-Switched Capacitors (TSC)), as shown in Figure 2-6.

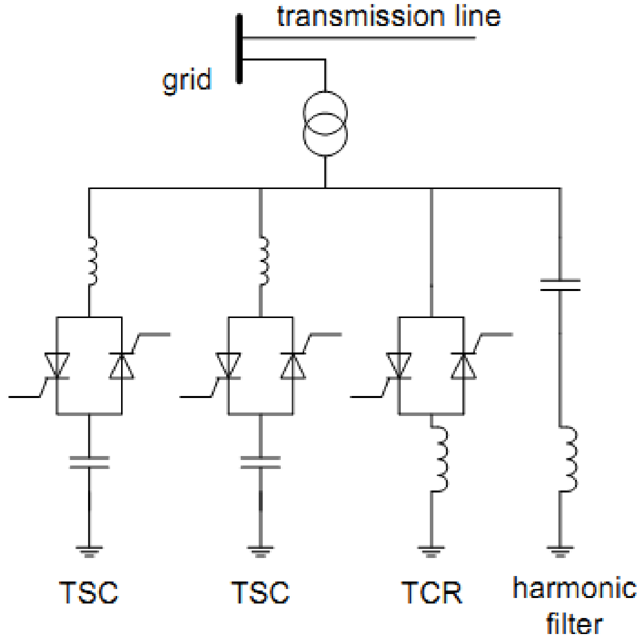


Figure 2-6: Typical SVC configuration

The TSC and TCR consist of an inverse-parallel thyristor in series with a capacitor or inductor. TSC utilizes inverse-parallel thyristors instead of mechanical connectors to allow capacitors to be quickly switched on and off. A small inductor in series is used to limit inrush currents on the occasions when severe transience occurs, for instance during the initial charging of a capacitor. TCR employs the firing angle control to the thyristors to vary the current thereby controlling the shunt reactance of the TCR. The firing angle varies from a 90◦ delay, for continuous conduction, to 180◦ delay, for minimum conduction, as shown in Figure 2-7. A TCR combined with TSCs is able to provide continuously variable Var injection or absorption.

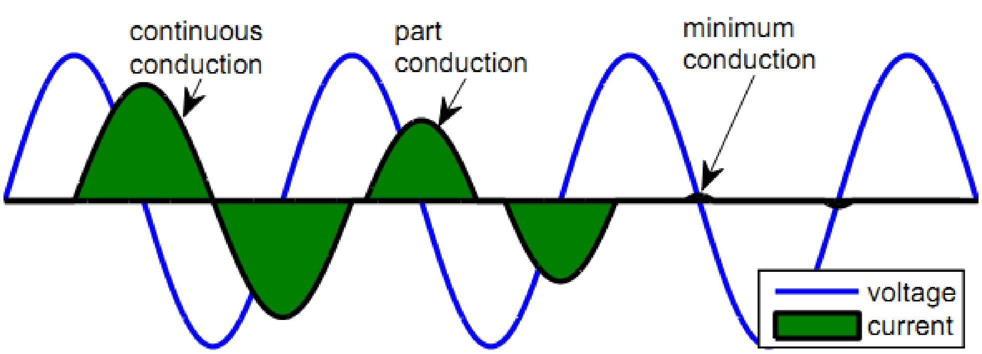


Figure 2-7: Voltage and current waveforms of a TCR for different firing angles

The SVC acts as a controllable reactor (or capacitor), and the supplied reactive power is proportional to the square of the bus voltage. Accordingly, the SVC is less effective in providing reactive power when the bus voltage is low. In addition, the current provided by the SVC contains large amounts of harmonics as shown in Figure 2-7, therefore a filter with low cut-off frequency is required to improve the waveform quality [1, 2].

2.4.2 STATCOM

A static synchronous compensator (STATCOM) is basically a VSC that is connected between a grid and the ground through a coupling inductance, as shown in Figure 2-8.The STATCOM acts as an AC voltage source and has characteristics similar to a synchronous condenser (a synchronous generator that is running idle and used for reactive compensation) . The STATCOM injects an AC current in quadrature (leading or lagging) with the grid voltage, and emulates capacitive or inductive impedance at the point of connection. If the voltage generated by the STATCOM is less than the grid voltage, it will act as an inductive load and withdraw reactive powers from the system. Conversely, when the STATCOM voltage is higher than the grid voltage, it will act as a capacitive Figure 2-8: load and provide reactive power to the grid. Compared to the synchronous condenser, the STATCOM is a Power Electronic-based device without inertia and therefore has a faster dynamic response [2].

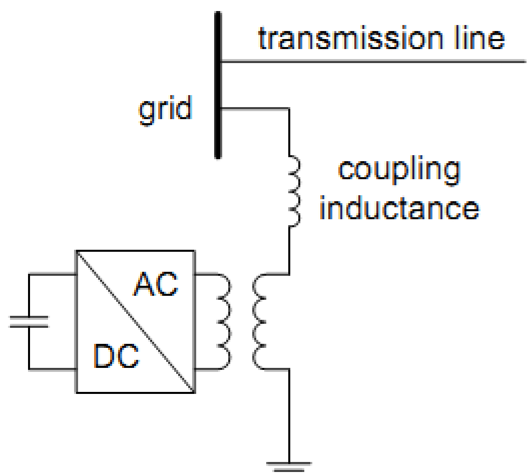


Fig 2-8 STATCOM configuration

The DC VSC is the most common type of converter that used for the STATCOM and the DC voltage source can be a capacitor. By using a multi-level, multiphase, or Pulse-Width Modulated (PWM) converter, the current distortion of the STATCOM outputs can be sufficiently reduced and the STATCOM may even require no filtering. Figure 2-9 shows the waveforms of a voltage generated by a five-level STATCOM and the corresponding current.

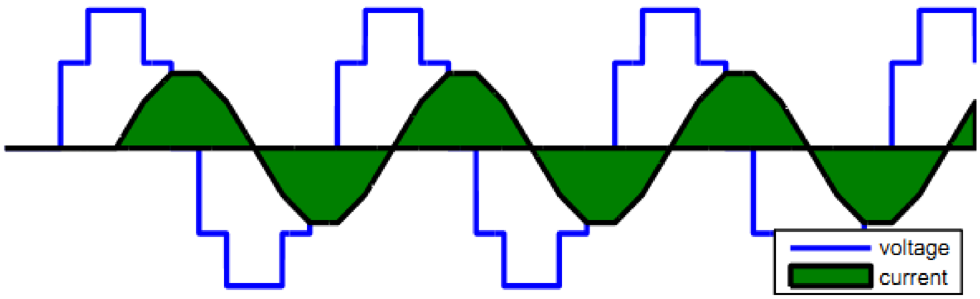


Figure 2-9: Voltage and current waveforms generated by a five-level STATCOM

As shown, the STATCOM has better characteristics than the SVC, because the output contains fewer harmonics. Also the reactive power provision of the STATCOM is independent from actual grid voltage magnitude. However, the STATCOM is more complex than the SVC due to the inclusion of a VSC. Accordingly, the STATCOM is more expensive than the SVC, especially for the high-voltage transmission lines [2].

2.5 SERIES DEVICES

The approach of series devices is to install variable impedance in series with the transmission line, as shown in Figure 2-10.

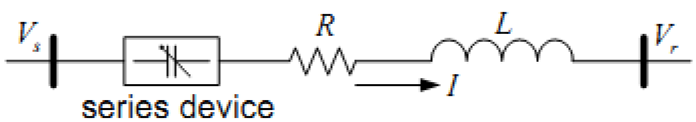


Figure 2-10: Series device operating principle

The series device can be inductive or capacitive, thereby varying the line impedance to control the power flow according to the equation:

$$P_r = \frac{|V_r||V_s|}{|X|}\sin\theta$$

$$Q_r = \frac{|V_r||V_s|}{|X|}\cos\theta - \frac{|V_r|^2}{X} \qquad (2.6)$$

In the case of a capacitive device, a fraction of the reactance of the transmission line is balanced, which increases the power flow. When the series device acts as inductive, the reactance will be increased thereby limiting the power flow. Besides controlling the power flow, series devices can also be used to improve angular stability and voltage stability

Series devices have been developed, including fixed or mechanical switched compensators to thyristor controlled series compensators and VSC-based devices. The configurations of the fixed and mechanical switched compensators are shown in Figure 2-11. Due to their relatively simple operation, slow response and stepwise adjustment, they will not be discussed in this section [2].

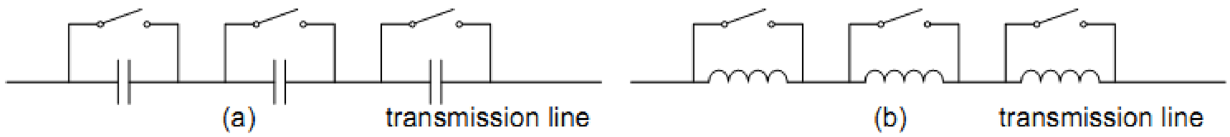


Figure 2-11: Configurations of mechanical switched series devices: (a) capacitor; (b) inductor

2.5.1 TSSC

A Thyristor Switched Series Capacitor (TSSC) uses inverse-parallel thyristors in parallel with a segment of the series capacitor bank to rapidly insert or remove portions of the bank in discrete steps, as shown in Figure 2-12. Because the TSSC employs thyristors to switch the capacitor banks, it has a faster response than mechanically switched compensators. However, as the TSSC also has stepwise adjustment, it is not widely used in applications. In addition, the TSSC can only insert capacitance into lines and cannot limit line currents [2].

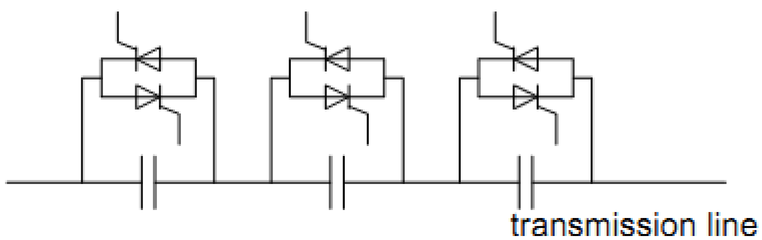


Figure 2-12: TSSC configuration

The configuration of a TCSC is shown in Figure 2-13.

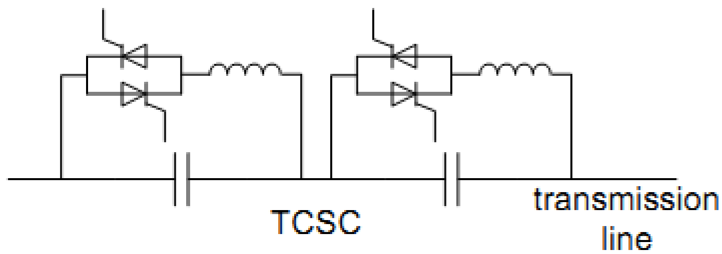


Figure 2-13: TCSC configuration

The idea behind TCSC is to use inverse-parallel thyristors to control the reactance of the TCR branch. Together with the fixed capacitor, the total impedance of the TCSC is adjusted. The line impedance adjustment of the TCSC can be done within one cycle, thereby providing a faster power flow control than mechanical switched devices.

As shown in Figure 2-7, the branch within the TCR will cause low frequency harmonic currents. The capacitor bank provides a low impedance path for the harmonics current; therefore, most of the harmonic currents will circulate within the TCR and the capacitor branches. However, there will still be a small amount of harmonics leaking into the transmission line. Also, as the voltage injected by the TSSC and TCSC is proportional to the line current, during low loading conditions, TSSC and TCSC are not effective [2].

2.5.2 SSSC

The Static Synchronous Series Compensator (SSSC) comprises a converter which is connected in series with the transmission line, as shown in Figure 2-14. The SSSC operates without external power source as a series compensator whose output voltage is in quadratic, and controllable independently of the line current. The purpose of this is to increase or decrease the total reactive voltage drop across the line, thereby controlling the energy flow. A small part of the injected voltage that is in phase with the line current offset the losses in the converter.

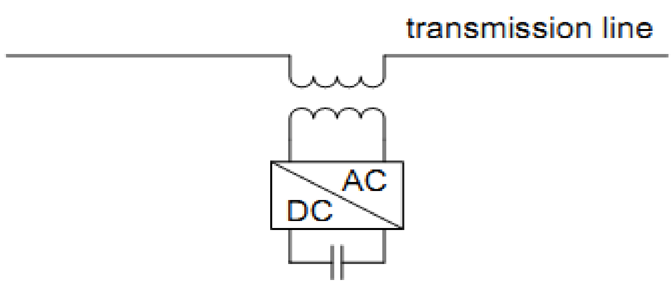


Figure 2-14: SSSC configuration

Because the voltage that is injected by the VSC within the SSSC is not related to the line current and can be controlled independently, the SSSC is effective for both low and high load conditions. Similar to the STATCOM, the output of the SSSC contains fewer harmonics than thyristor-based devices. Although the configuration of SSSC is similar to a STATCOM, the SSSC is more complicated in reality. It requires platform mounting for high-voltage isolations and complex bypass protection in case of failures [1, 2].

2.5.3 DSSC

The Distributed Static Series Compensator (DSSC), which keeps the functionality of the SSSC with higher reliability and lower cost. The concept of DSSC uses a large number of units with low power ratings instead of one controller with a large power rating, as shown in Figure 2-15.

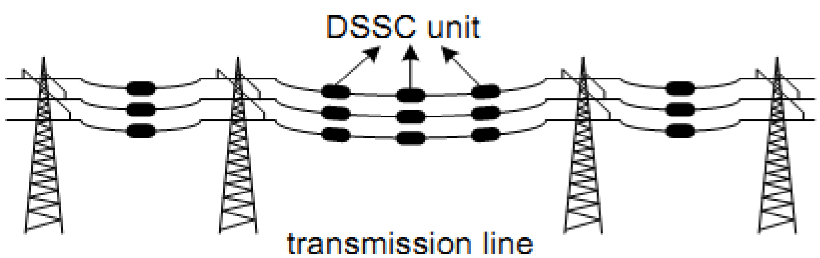


Figure 2-15: Transmission line with the DSSC units

A DSSC unit consists of multiple low-rate VSCs, that are connected to the transmission line single turn transformers. The transformer once, using the transmission line and its secondary winding and a controllable voltage injected directly into the line. Most of the injected voltage DSSC unit is in quadrature with the line current, to emulate inductive or capacitive impedance. A small part of the voltage is in phase with the line current and serves to self-power the unit and DSSC cover losses.

The DSSC remotely controlled via wireless communication or PLC. The setting of DSSC unit is shown in Figure 2-16. The uniqueness of the DSSC is at a relatively low cost and high reliability. As units DSSC devices are single phase fl floating lines, high voltage isolation between the phases are avoided. The units can be easily applied to any voltage level of the transmission because they do not require line-ground insulation support. The power and voltage of each unit is small. In addition, the units are fixed on the transmission lines, requiring no additional land, thus eliminating their mark. DSSC redundancy provides uninterrupted operation during a single module failure, resulting in a lower reliability than other FACTS devices cost [19].

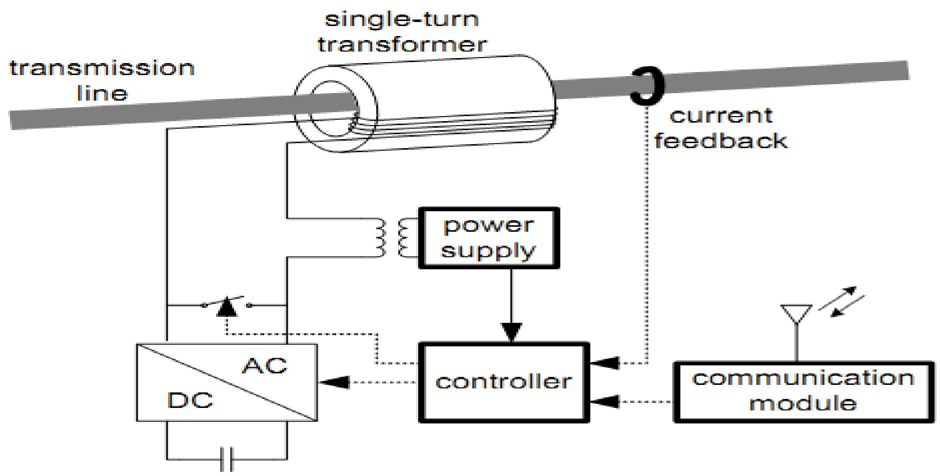


Figure 2-16: DSSC module configuration [19]

2.6 COMBINED DEVICES

In this section, three combined devices will be introduced: the Phase Shifting Transformer (PST), the Unified Power Flow Controller (UPFC) and the Interline Power Flow Controller (IPFC).

2.6.1 PST

The Phase Shifting Transformer (PST) is a specialized form of transformer used to control the active power flow of transmission networks. A PST typically consists of a shunt transformer with a tap changer and a series transformer. The principle of PST is that the series transformer inserts a voltage, which is obtained from the other phases of the shunt transformer. The injected voltage is in quadrature with the phase voltage and causes a phase angle shift across the transformer, thereby varying the transmission angle.

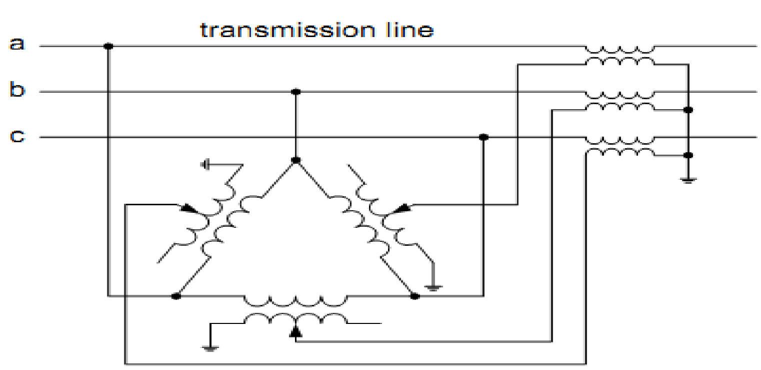


Figure 2-17: Configuration of a simple PST

By changing the taps of the shunt transformer, the magnitude of the quadrature voltage can be controlled and thus the voltage phase shifts across the PST. Figure 2-17 illustrates the configuration of a simple PST. The major drawbacks associated with PSTs are slow response due to the inherent inertia of the mechanical tap changer, its limited lifetime and the frequent maintenance required due to mechanical wear and oil deterioration. There are also PSTs based on Power Electronics, but no such PST is in service, mainly due to the complex short circuit current protection that is required [1].

2.6.2 UPFC

The Unified Power Flow Controller (UPFC) is comprised of a STATCOM and a SSSC, and it is coupled via a common DC link to allow bi-directional flow of active power between the shunt output terminals of the STATCOM and the series output terminals of the SSSC. Each converter can independently generate or absorb reactive power at its own AC terminal. The two converters are operated from a DC link provided. The configuration of a UPFC is shown in Figure 2-18 [2].

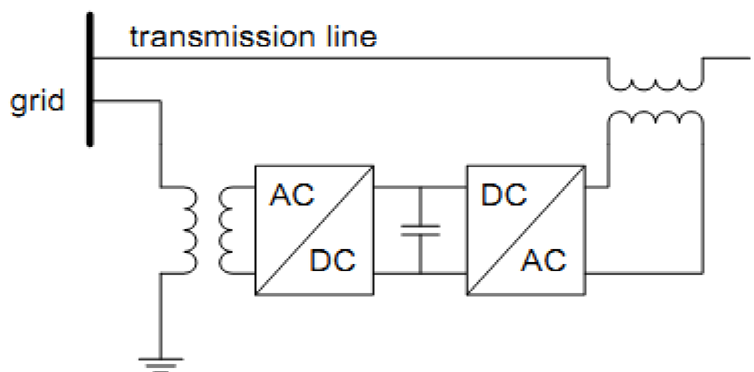


Figure 2-18: UPFC configuration [2]

The series converter performs the main function of the UPFC by injecting a voltage with controllable magnitude and phase angle in series with the transmission line. It is controlled to provide series compensation for active and reactive concurrently without an external power. Through the series voltage injection without angular limitation, the UPFC is able to control, concurrently or selectively, the power transmission angle, and the line impedance, or alternatively, active and reactive power flow through the line .

The voltage injected by the series converter results in exchange for the active and reactive power between the series converter and the transmission line. The reactive power is generated internally by the series converter (as SSSC), and active power is supplied by the shunt converter is transported through the common DC link.

The basic function of the shunt converter is to supply or absorb the real power demanded by the series converter. The shunt converter controls the DC capacitor voltage by generating or absorbing real power from the bus, so it acts as a synchronous source in parallel with the system.

Like the STATCOM, the adjustable bypass can also provide independently controlled reactive compensation for the bus. Considering its control capability, the UPFC can have the functions:

• Voltage regulation by continuously varying in-phase/anti-phase voltage injection that is similar to a tap-change transformer.

• Series reactive compensation by injecting a voltage that is in quadrature to the line current. Functionally, this is similar to an SSSC that can provide a controllable inductive and capacitive series compensation.

• Phase shifting by injecting a voltage with an angular relationship with respect to the bus voltage. By varying the magnitude of this voltage, the phase shift can be controlled.

The listed functions of the UPFC can be executed simultaneously, which makes the UPFC the most powerful PFCD. However, due to high voltage VSCs and corresponding protection requirements, UPFC is quite expensive, which limits its practical application [1, 2].

2.7 IPFC

The Interline Power Flow Controller (IPFC) consists of the two (or more) series converters in different transmission lines that are inter-connected via a common DC link, as shown in Figure 2-19. Unlike other FACTS devices that aim to control the parameter of a single transmission line, the IPFC is conceived for the compensation and control of power flow in a multi-line transmission system.

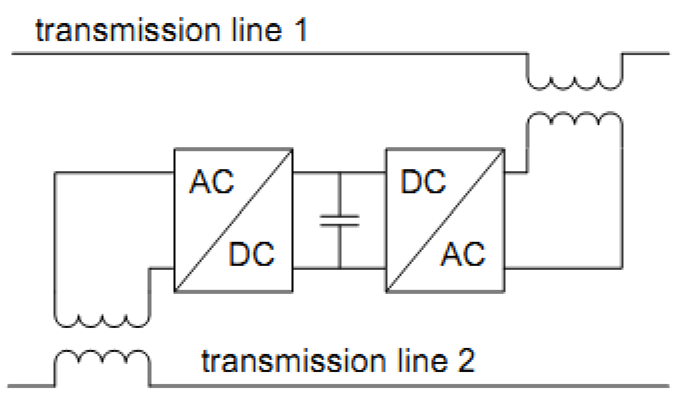


Figure 2-19: IPFC configuration [16]

Each converter can provide series reactive compensation of its own line, just as an SSSC can. As the converters can exchange active power through their common DC link, the IPFC can also provide active compensation. This allows the IPFC to provide both active and reactive compensation for some of the lines and thereby optimize the utilization of the overall transmission system. Note that the active power supplied to one line is taken from the other lines.

If required, the IPFC can be complemented with an additional shunt converter to provide active power from a suitable shunt bus [16].

From above discussion of power flow control and PFCDs it can be concluded that the DSSC have relatively low cost and high reliability. However, the control capability of the DSSC is limited because it can only inject reactive power. It is found that the combined PFCDs based on VSCs have the best capability of power flow control, and are therefore the most suitable device for the future network. However, their high cost and complexity become the bottleneck for their application in practice.

Chapter 3

DISTRIBUTED POWER FLOW CONTROLLER

3.1 INTRODUCTION

In the previous chapter, an overview was given of mechanical and PE-based PFCDs. Because of high control capability, the PE-based combined PFCs, specifically UPFC and IPFC are suitable for the future power system. Due to their high cost and the susceptibility to failures UPFC and IPFC are not widely applied in practice.

After studying the failure mode of the combined FACTS devices, it is found that a common DC link between converters reduces the reliability of a device, because a failure in one converter will pervade the whole device though the DC link. By eliminating this DC link, the converters within the FACTS devices are operated independently, thereby increasing their reliability [19].

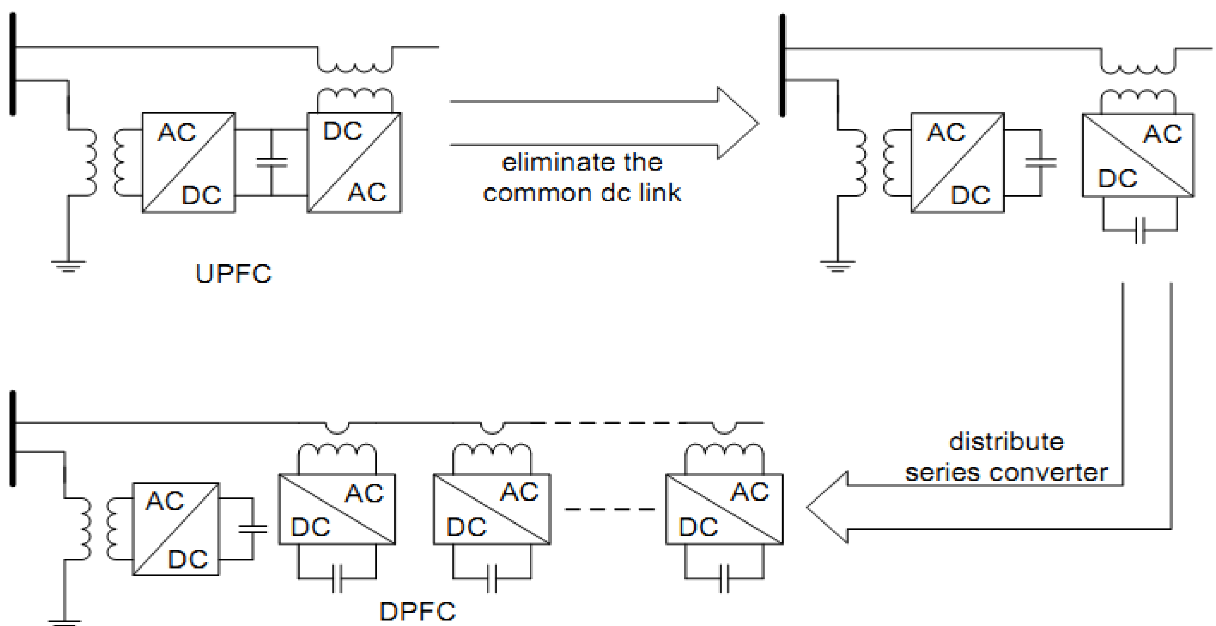


Figure 3-1: Flowchart from UPFC to DPFC

The elimination of the common DC link also allows the DSSC concept to be applied to series converters. In that case, the reliability of the new device is further improved due to the redundancy provided by the distributed series converters. In addition, series converter distribution reduces cost because no high-voltage isolation and high power rating components are required at the series part. By applying the two approaches –eliminating the common DC link and distributing the series converter, the UPFC is further developed into a new combined FACTS device: the Distributed Power Flow Controller (DPFC) [19], as shown in Figure 3-1.

In this chapter, principle and proprieties of the DPFC has been presented, followed by a steady-state analysis. During the analysis, the control capability and the influence of the DPFC on the network are presented.

3.2 DISTRIBUTED POWER FLOW CONTROLLER (DPFC)

In this section, DPFC topology and operating principle are introduced. The shunt converter is similar to a STATCOM, while the series converter uses the DSSC concept, multi-phase converters is used instead of a three-phase inverter. Each converter within the DPFC is independent and has its own DC capacitor to provide the required DC voltage [19, 21, 22].

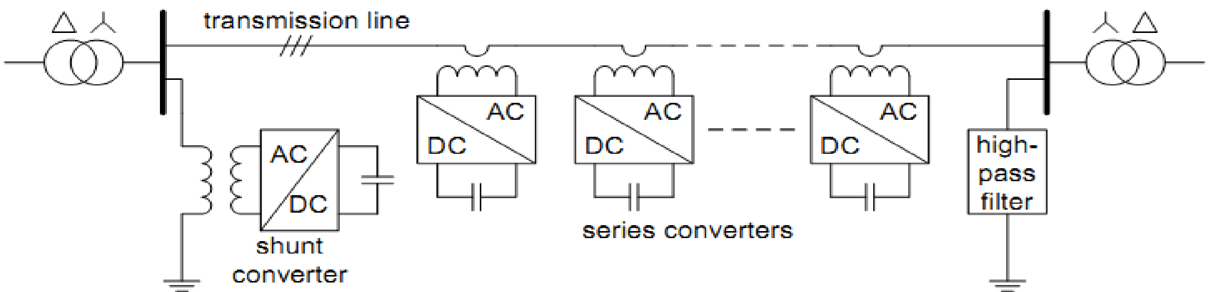


Figure 3-2 configuration of the DPFC [19]

As shown, in addition to the key components of the series and shunt - converting a DPFC also requires a high pass filter which is connected in shunt across the transmission line and a transformer Y-Δ on each side of line. The reason of these additional components will be explained later. The unique ability to control the UPFC is given by the connection back to back between the shunt and series converters, allowing the active power to share freely. To ensure DPFC has the same control capability as the UPFC, a method that allows the exchange of active power between converters with DC link removed is required [19].

3.2.1 DPFC operating principle

Active exchange of energy removed from the intermediate circuit DPFC Inside, the transmission line has a common connection between the ports of AC shunt and series converters. Therefore, it is possible to exchange active power through AC ports. The method is based on the theory of non-sinusoidal power components.

According to Fourier analysis, non-sinusoidal voltage and current can be expressed as the sum of sinusoidal functions of frequencies with amplitudes. The active power resulting from this non-sinusoidal voltage or current is defined as the mean value of the product of the voltage and current. From the integrals of all the cross product terms with frequencies are zero the active power can be expressed by:

$$P = \sum_{i=1}^{\infty} V_i \, I_i \cos \emptyset_i \quad (3.1)$$

Where V_i and I_i are the voltage and current at i^{th} harmonic frequency respectively, and φ_i is the corresponding angle between the voltage and current. Equation (3.1) shows that active frequencies powers are independent of each other and the voltage or current at a frequency has no influence on the active power at other frequencies

According to the required amount of active power at the fundamental frequency, DPFC series converters generate a voltage at the harmonic frequency, thereby absorbing the active power from harmonic components. Neglecting losses, the active power at the fundamental frequency is equal to the absorbed power at the harmonic frequency. For a better understanding, Figure 3-3 shows how the active power between the shunt and series converters in the system DPFC exchanged.

The high pass filter within the core blocks DPFC frequency components and harmonic components allows to pass, thereby providing a return path for the harmonic components. The shunt and series converters, the high pass filter and the ground form a closed harmonic current circuit [19].

Using third harmonic components

Due to the unique characteristics of the 3^{rd} harmonic frequency components in a system of three phases, the 3^{rd} harmonic to exchange active power in the selected DPFC. In a three phase system, the 3^{rd} harmonic for each phase is identical, which means that components are 'zero sequence. Because the harmonic zero sequence can be blocked naturally by Y-Δ transformers and these are widely incorporated into the energy systems (such as medium voltage change), no additional filter necessary to prevent leakage harmonic.

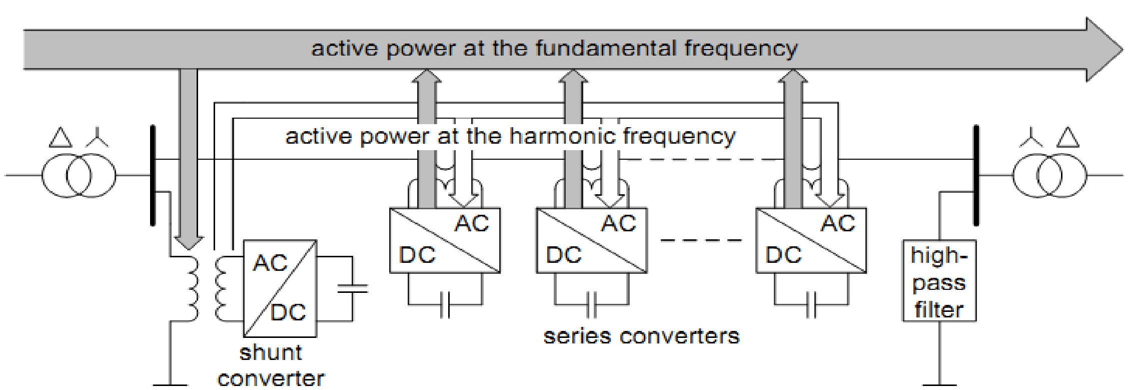


Figure 3-3: Active power exchange between DPFC converters [19]

By using the zero-sequence harmonic, the costly filter can be replaced by a cable that connects the neutral point of the Y-Δ transformer on the right side in Figure 3-2 with the ground. Because the Δ-winding appears open-circuit to the 3rd harmonic current, all harmonic current will flow through the Y-winding and concentrate to the grounding cable as shown in Figure 3-4. Therefore, the large high-pass filter is eliminated [19].

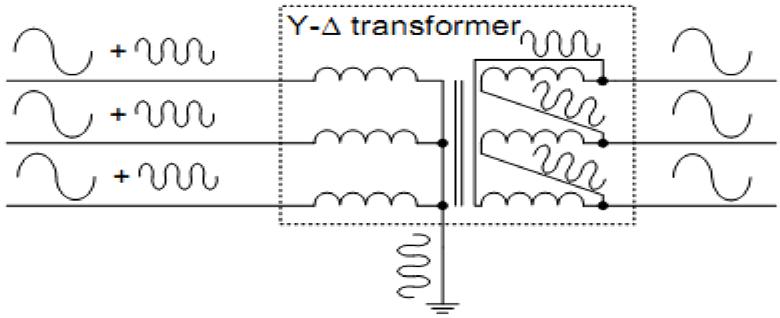


Figure 3-4: Utilize grounded Y-Δ transformer to filter zero-sequence harmonic [19]

Another advantage of using the 3rd harmonic to exchange active power is that the grounding of the Y-Δ transformers can be used to route the harmonic current in a meshed network. If the network requires the harmonic current to flow through a specific branch, the neutral point of the Y-Δ transformer in that branch, at the side opposite to the shunt converter, will be grounded and vice versa. Figure 3-5 shows a simple example of routing the harmonic current by using the grounding of the Y-Δ transformer. Because the floating neutral point is located on the transformer of the line without the series converter, it is an open-circuit for 3rd harmonic components and therefore no 3rd harmonic current will flow through this line.

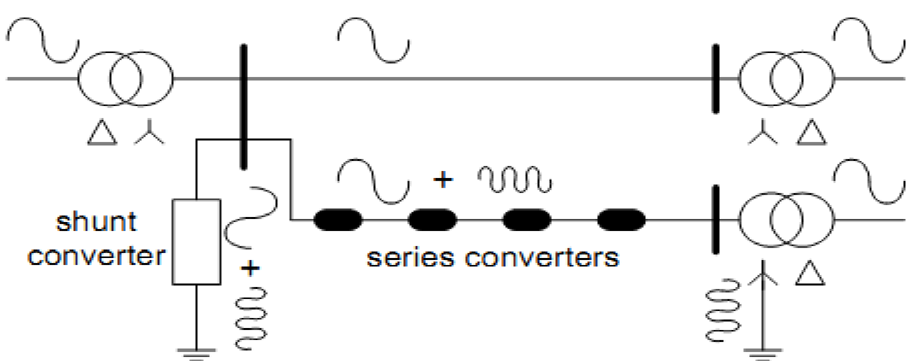


Figure 3-5: Route the harmonic current by using the grounding of the Y-Δ transformer [19]

The harmonic at the frequencies like 3rd, 6th, 9th... are all zero-sequence and all can be used to exchange active power in the DPFC. However, the 3rd harmonic is selected, because it is the lowest frequency among all zero-sequence harmonics [17, 19]. The relationship between the exchanged active power at the ith harmonic frequency P_i and the voltages generated by the converters is expressed by the well known the power flow equation and given as:

$$P_i = \frac{|V_{sh,i}||V_{se,i}|}{X_i}\sin(\theta_{sh,i} - \theta_{se,i}) \qquad (3.2)$$

where X_i is the line impedance at i^{th} frequency, $|V_{sh,i}|$ and $|V_{se,i}|$ are the voltage magnitudes of the i^{th} harmonic of the shunt and series converters, and '$\theta_{sh,i} - \theta_{se,i}$' is the angle difference between the two voltages.

3.2.2 DPFC Control

To control multiple converters, a DPFC consists of three types of controllers: central control, shunt control and series control, as shown in Figure 3-6.

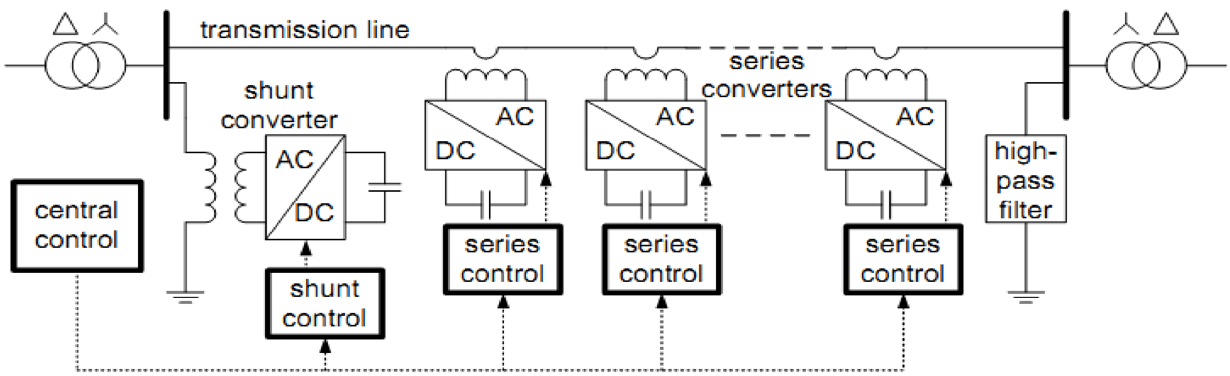


Figure 3-6: DPFC control block diagram [19]

• ***Central control***: The central control generates the reference signals for both the shunt and series converters of the DPFC. According to the system requirements, the central control gives corresponding voltage reference signals for the series converters and reactive current signal for the shunt converter. All the reference signals generated by the central control concern the fundamental frequency components [19].

• ***Series control***: Each series converter has its own series control. The controller is used to maintain the capacitor DC voltage of its own converter, by using 3^{rd} harmonic frequency components, in addition to generating series voltage at the fundamental frequency as required by the central control [19].

• ***Shunt control***: The objective of the shunt control is to inject a constant 3^{rd} harmonic current into the line to supply active power for the series converters [19].

At the same time, it maintains the capacitor DC voltage of the shunt converter at a constant value by absorbing active power from the grid at the fundamental frequency and injecting the required reactive current at the fundamental frequency into the grid.

The detailed schematics and designs of the DPFC control will be introduced in following chapters.

3.2.3 Variation of the Shunt Converter

In the DPFC, the shunt converter should be a relatively large three-phase converter that generates the voltage at the fundamental and 3rd harmonic frequency simultaneously. A conventional choice would be a three-leg, three-wire converter. However, the converter is an open circuit for the 3rd harmonic components and is therefore incapable of generating a 3rd harmonic component. Because of this, the shunt converter in a DPFC will require a different type of 3-phase converter. There are several 3-phase converter topologies that can generate 3rd harmonic frequency components, such as multi-leg, multi-wire converters or three single-phase converters. These solutions normally introduce more components, thereby increasing total cost.

A new topology for the DPFC shunt converter is proposed. The topology utilizes the existing Y-Δ transformer to inject the 3rd harmonic current into the grid. A single-phase converter is connected between the transformer's neutral point and the ground and injects a 3rd harmonic current into the neutral point of the transformer. This current evenly spreads into the 3-phase line through the transformer. The converter can be powered by an additional back-to-back converter connected to the low-voltage side of the transformer. The circuit scheme of this topology is shown in Figure 3-7.

For a symmetrical system, the voltage potential at the neutral point and fundamental frequency is zero. Accordingly, the single-phase converter only handles the 3rd harmonic voltages, which are much lower than the voltage at the fundamental frequency. As the single-phase converter is only used to provide active power for the series converter, the voltage and power rating are small. In addition, the single-phase converter uses the already present Y-Δ transformer as a grid connection. The single-phase converter is powered by another converter through a common DC link. In the case of the system with

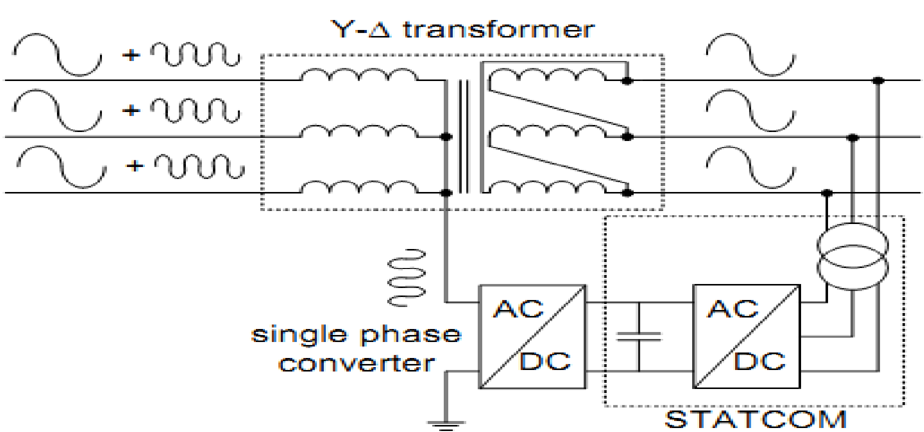


Figure 3-7: DPFC shunt converter configuration

a STATCOM, the single-phase converter can be directly connected back-to-back to the DC side of the STATCOM[17], as shown in Figure 3-7.

3.2.4 Advantages and Limitation of the DPFC

The DPFC inherits all their advantages:

• High controllability

• High reliability

• Low cost:

The power rating of each converter is also low. Because of the large number of the series converters; they can be manufactured in series production. If the power system is already equipped with the STATCOM, the system can be updated to the DPFC with only low additional costs.

However, there is a drawback to using the DPFC:

• Extra currents: Because the exchange of power between the converters takes place through the same transmission line as the main power, extra currents at the 3rd harmonic frequency are introduced. These currents reduce the capacity of the transmission line and result in extra losses within the line and the two Y-Δ transformers. However, because this extra current is at the 3rd harmonic frequency, the increase in the RMS value of the line current is not large and through the design process can be limited to less than 5% of the nominal current [1, 2].

3.3 DPFC STEADY-STATE ANALYSIS

In this section, the steady-state behavior of the DPFC is analyzed. This section starts with the simplification of DPFC, followed by the analysis of the circuit at the fundamental frequency. The 3rd harmonic circuit is examined with regards to the active power required by the fundamental frequency components. The section ends by considering the relationship between the ratings of the DPFC converters and the corresponding capability of power flow control [19].

3.3.1 DPFC Simplification and Equivalent Circuit

To simplify the DPFC, the converters are replaced by controllable voltage sources in series with impedance. Since each converter generates voltages at two different frequencies, they are represented by two series connected controllable voltage sources, one at the fundamental frequency and the other at the 3rd harmonic frequency. Assuming the converters and the transmission line have no loss, the total active power generated by the two voltage sources will be zero. The multiple series converters are simplified as one large converter with a voltage that is equal to the voltages of all series converters. Consequently, a simplified representation of the DPFC is shown in Figure 3-8.

The DPFC is placed in a two-bus system with the sending end and the receiving end voltages V_s and V_r. The transmission line is represented by an inductance 'L' with the line current 'I'. The voltage injected by all the DPFC series converters is $V_{se,1}$ and $V_{se,3}$ at the fundamental and 3rd harmonic frequencies, respectively. The shunt converter is connected to the sending bus through the inductor L_{sh} and generates the voltage $V_{sh,1}$ and $V_{sh,3}$, and the current injected by the shunt converter is I_{sh}. The active and reactive power flows at the receiving end are P_r and Q_r. Arrow 'A' represents the active power exchange within the converter itself and arrow 'B' indicates the power exchange between the shunt and the series converter through the 3rd harmonic [19].

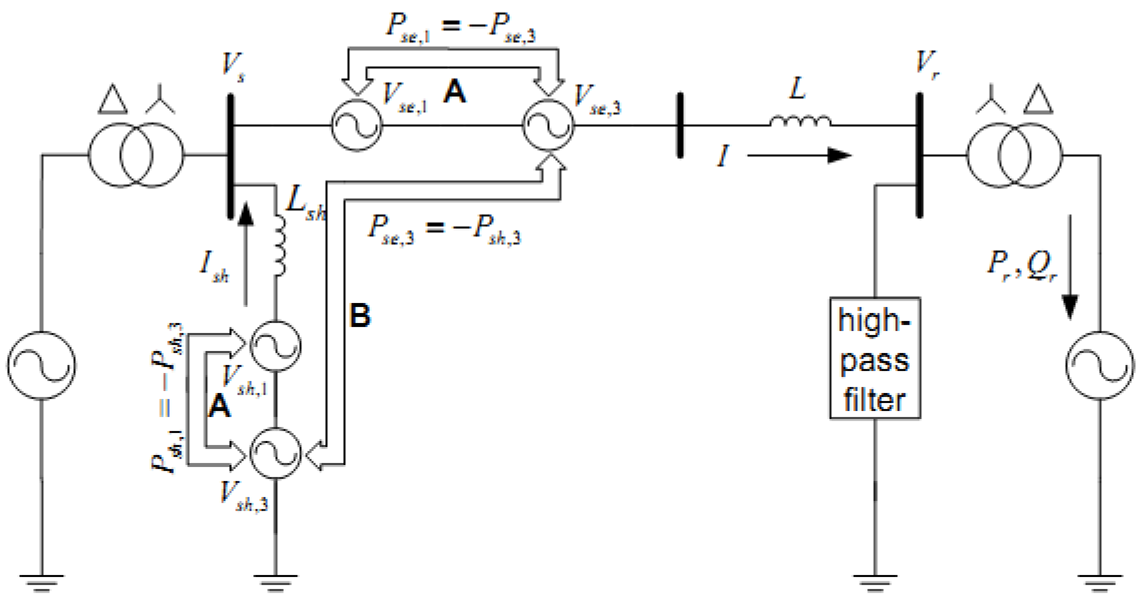


Figure 3-8: DPFC simplified representation [19]

For an easier analysis it shows both the fundamental frequency and 3rd harmonic frequency components in Figure 3-8 can be further simplified by splitting it into two circuits at different frequencies. Both circuits are isolated from each other as shown in Figure 3-9.

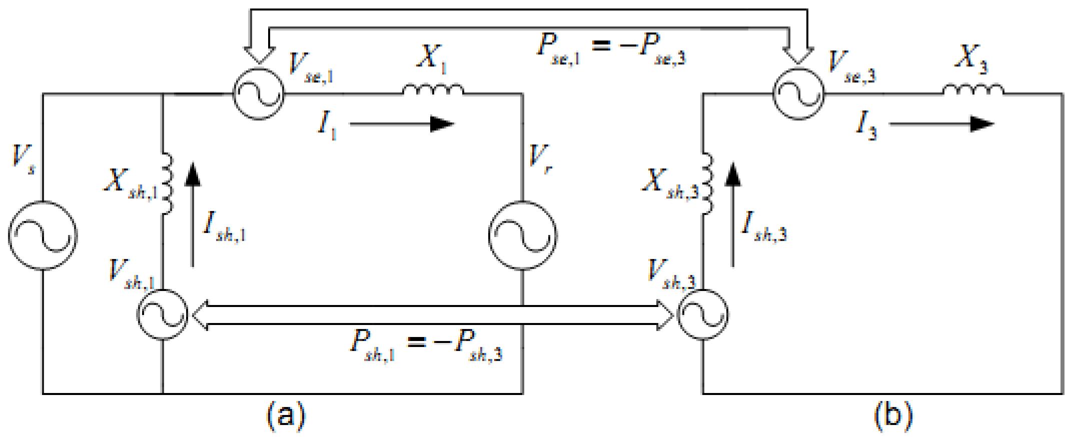


Figure 3-9 equivalent circuit of DPFC: (a) for the fundamental frequency; (b) the 3rd harmonic frequency [19]

These two circuits are linear circuits and can be analyzed separately, where each circuit contains only single-frequency components.

3.3.2 Fundamental Frequency Circuit

In this section, the DPFC circuit is analyzed. The control capability of the DPFC is examined and the relationship between the exchanged active power and control range is found [19].

Capability of power flow control

The power flow of the DPFC can be illustrated by the active power P_r and reactive power Q_r at the receiving end, as shown in Figure 3-9(a). The active and reactive power flow can be expressed as follows:

$$P_r + jQ_r = V_r . I_1^*$$

$$= V_r \left(\frac{V_s - V_r - V_{se,1}}{jX_1}\right)^* \qquad (3.3)$$

where the phasor values are used for voltages and currents, '∗' means the conjugate of a complex number and $X_1 = \omega_1 L$ is the line impedance at the fundamental frequency. The power flow (P_r, Q_r) consists of two parts: the power flow without DPFC compensation (P_{r0}, Q_{r0}) and the part that is varied by the DPFC $(P_{r,c}, Q_{r,c})$. The power flow without DPFC compensation (P_{r0}, Q_{r0}) is given by:

$$P_{r0} + jQ_{r0} = V_r . \left(\frac{V_s - V_r}{jX_1}\right)^* \qquad (3.4)$$

Accordingly, by substituting (3.4) into (3.3), the DPFC control range on the power flow can be expressed as:

$$P_{r,c} + jQ_{r,c} = \frac{V_r.V_{se,1}^*}{jX_1} \tag{3.5}$$

The voltage $V_{se,1}$ can be rotated 360°, the control range of the DPFC is a circle in the PQ-plane, and its center is the uncompensated power flow (P_{r0},Q_{r0}) and radius is equal to ($|V_r||V_{se,1}|/X_1$). The control capability of the DPFC is shown in the following formula:

$$(P_r - P_{r0})^2 + (Q_r - Q_{r0})^2 = \left(\frac{V|V_{se,1}|}{X_1}\right)^2 \tag{3.6}$$

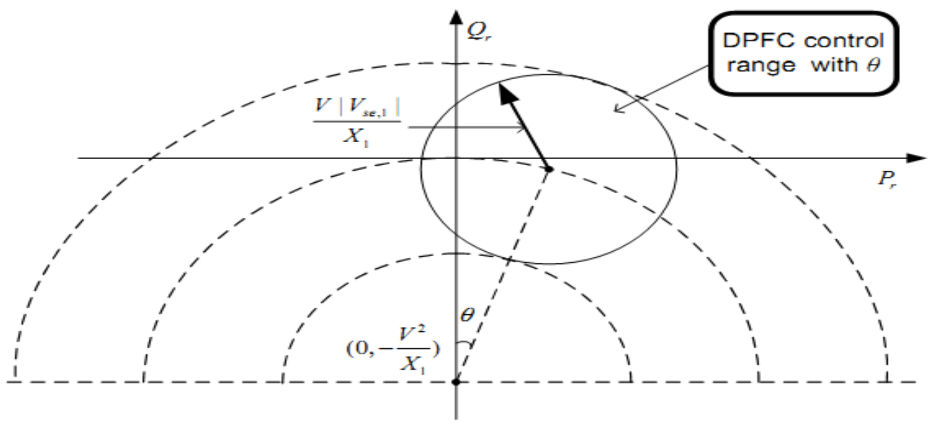


Figure 3-10: DPFC active and reactive power control range with the transmission angle ‘θ’ [19]

Active power required by the series converters T_o inject a 360° rotatable voltage, an active and reactive power at the fundamental frequency has to be supplied to the series converter, which is given as:

$$P_{se,1} + jQ_{se,1} = V_{se,1}.I_1^*$$

$$= V_{se,1}.\frac{S_r}{V_r} \tag{3.7}$$

The voltage injected by the series converter $V_{se,1}$ can be solved from (3.3), which is given as:

$$V_{se,1} = \left[\frac{(S_r - S_{r0}).jX_1}{V_r}\right]^* \tag{3.8}$$

By substituting (3.8) into (3.7), the power requirement can be written as:

$$P_{se,1} + jQ_{se,1} = \left[\frac{(S_r - S_{r0}).jX_1}{V_r}\right]^*.\frac{S_r}{V_r}$$

$$= \frac{jX_1}{|V_r|^2}.(S_r S_{r0} - |S_r|^2) \quad (3.9)$$

The reactive power is provided by the series converter locally and the active power is indirectly supplied by the shunt converter through the 3rd harmonic component. This active power requirement is given by:

$$P_{se,1} = Re\left[\frac{jX_1}{|V_r|^2}.(S_r S_{r0} - |S_r|^2)\right]$$

$$= \frac{jX_1}{|V_r|^2}.|S_r||S_{r0}|\sin(\varphi_{r0} - \varphi_r) \quad (3.10)$$

Consequently, the required active power by the series converter can be written as:

$$P_{se,1} = CA_{(0,r0,r)} \quad (3.11)$$

Where, the coefficient $C = 2X_1/|V_r|^2$,

A(0,r0,r) is the area of the triangle (0, S_{r0}, S_r).

The angle difference between ϕ_{r0} and ϕ_r can either positive or negative, and the sign shows the direction of the active power for the DPFC series converters. A positive sign indicates that the series converters generate active power. The active power requirement can vary and reaches its maximum when the vector '$S_r - S_{r0}$' is perpendicular to S_{r0} [19], as shown in Figure 3-12.

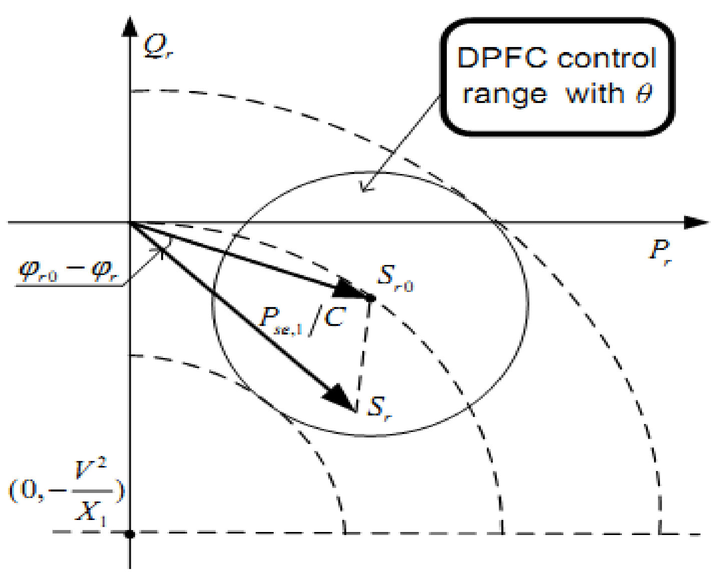


Figure 3-11: Relationship between $P_{se,1}$ and the power flow at the receiving end [19]

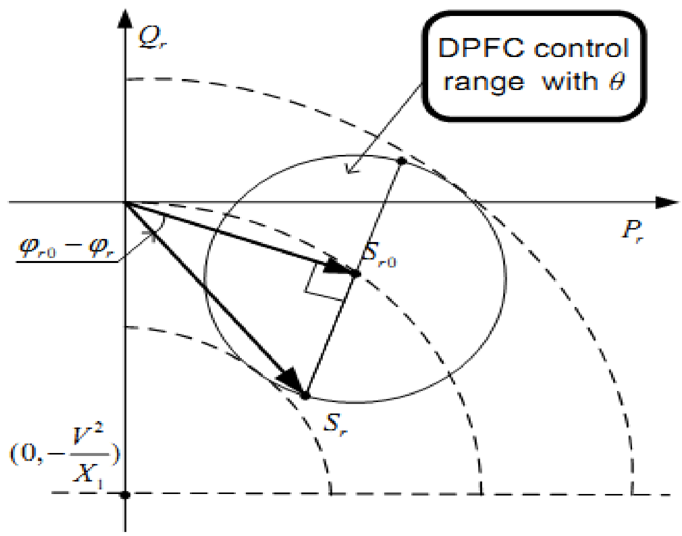


Figure 3-12: Maximum active power requirement for the series converters [19]

The control range of the DPFC is limited by this maximum value. According to the figure, the relationship between the maximum active power requirement and the power flow control range can be represented with the following equation:

$$P_{se,1,max} = \frac{|X_1||S_{r0}|}{|V_r|^2}\left|S_{r,c}\right| \tag{3.12}$$

where $|S_{r,c}|$ is the control range of the DPFC and given by:

$$\left|S_{r,c}\right| = max\left|P_{r,c} + jQ_{r,c}\right| \tag{3.13}$$

For a transmission line, the line impedance and the bus voltage can be assumed constant values. Accordingly, the control range is proportional to the maximum of the exchanged active power. The line impedance $|X_1|$ is normally around 0.05 pu. By assuming that the bus voltage $|V_r|$ and uncompensated power flow $|S_{r0}|$ is 1 pu, the value of exchanged active power can be determined as approximately 0.05 pu by using (3.12), allowing the DPFC to control 1 pu power flow.

3.3.3 Third Harmonic Frequency Circuit

The 3rd harmonic component within the DPFC system is used to exchange active and reactive power between the shunt and series converters. Therefore, the voltages and currents at the 3rd harmonic frequency are related to the required active power. For the series converters, there is:

$$\mathrm{Re}\left(V_{se,3}.I_3^*\right) = -P_{se,1} \tag{3.14}$$

From Figure 3-9(b), the power that is absorbed by the series converters at the 3rd harmonic frequency is given by:

$$P_{se,3} + jQ_{se,3} = V_{se,3}.I_3^*$$

$$= V_{se,3}\left(\frac{V_{sh,3} - V_{se,3}}{X_3'}\right)^* \quad (3.15)$$

where $X_3 = X_3 + X_{sh,3}$. By separating the real and imaginary parts, the absorbed active and reactive power at 3rd harmonic frequency can be expressed as:

$$P_{se,3} = \frac{|V_{se,3}||V_{sh,3}|}{X_3'}\sin\theta_3$$

$$Q_{se,3} = \frac{|V_{se,3}|}{X_3'}\left(|V_{sh,3}|\cos\theta_3 - |V_{se,3}|\right) \quad (3.16)$$

where θ_3 is the phase angle difference between the voltages $V_{sh,3}$ and $V_{se,3}$. For the series converters, any reactive power at the 3rd harmonic frequency results in unnecessary extra voltages and currents. Therefore, the reactive power flowing through the series converters at the 3rd harmonic frequency is controlled to be zero, which is $Q_{se,3} = 0$. It follows that the relationship between the voltages $V_{sh,3}$ and $V_{se,3}$ is:

$$|V_{se,3}| = |V_{sh,3}|\cos\theta_3 \quad (3.17)$$

By including (3.17) to (3.16),

$$P_{se,3} = \frac{|V_{sh,3}|^2}{X_3'}\cos\theta_3.\sin\theta_3 \quad (3.18)$$

When the angle 'θ_3' is 45◦, the maximum value of cos θ_3 sin θ_3 is equal to 1/2. Therefore, to efficiently supply the active power requirement $P_{se,1,max}$, the voltage injected by the shunt converter at the 3rd harmonic frequency should be:

$$|V_{sh,3,max}| \geq \sqrt{\left(2\,|P_{se,1,max}|.X_3'\right)} \quad (3.19)$$

Equation (3.17) shows that the maximum voltage of the series converters at the 3rd harmonic frequency should comply with:

$$|V_{se,3,max}| \leq |V_{sh,3,max}| \quad (3.20)$$

To transmit the same amount of active power, different combinations of voltage and current can be selected for different cases. If the DPFC is employed to boost the power flow through the transmission line, the DPFC can be designed to inject a small 3rd harmonic current, since the transmission line is likely to operate close to its thermal limits.

As compensation, more voltage at the 3rd harmonic frequency will be required, thereby involving more series converters. In the case where the DPFC is used to limit the line current, more losses at the 3rd harmonic frequency can be tolerated. Therefore, the DPFC can be designed to inject a high 3rd harmonic current and low voltage to reduce the number of series converters.

3.3.4 Control Range for DPFC

Each converter contains two voltage components at deferent frequencies in the DPFC generates, simultaneously. Because both voltage phasors are free with respect to their phase angles, the voltage rating is calculated by the equation given below.

$$V_{se,max} = \left|V_{se,1,max}\right| + \left|V_{se,3,max}\right| \tag{3.21}$$

In this operation active power requirement of the series converter can varies according to the voltage injected at the fundamental frequency. As the need is low, the series voltage will be smaller than $|V_{se,3,max}|$. Potential voltage between $V_{se,3}$ and $|V_{se,3,max}|$ is used to generate more voltage at the fundamental frequency, to increase control region for power flow of the DPFC. When '$S_{r,c}$' and S_{r0} is perpendicular to each other, series converters require maximum power, and the DPFC control region radius is given by:

$$\left|S_{r,c}\right| = \frac{|V_r|\left|V_{se,1,max}\right|}{X_1} \tag{3.22}$$

If $S_{r,c}$ is in the same line as S_{r0}, the series converters only provide the reactive compensation, and the boundary of the DPFC control region will extend to:

$$\left|S_{r,c}\right| = \frac{|V_r|\left(\left|V_{se,1,max}\right| + \left|V_{se,3,max}\right|\right)}{X_1} = \frac{|V_r|\left|V_{se,max}\right|}{X_1} \tag{3.23}$$

Consequently, the control region of the DPFC can be extended to an ellipse, as shown in Figure 3-13. As shown, the control range of the DPFC is extended from a circle to an ellipse. When the series converters of the DPFC require less active power, the converter can generate more voltages at the fundamental frequency, thereby increasing control range.

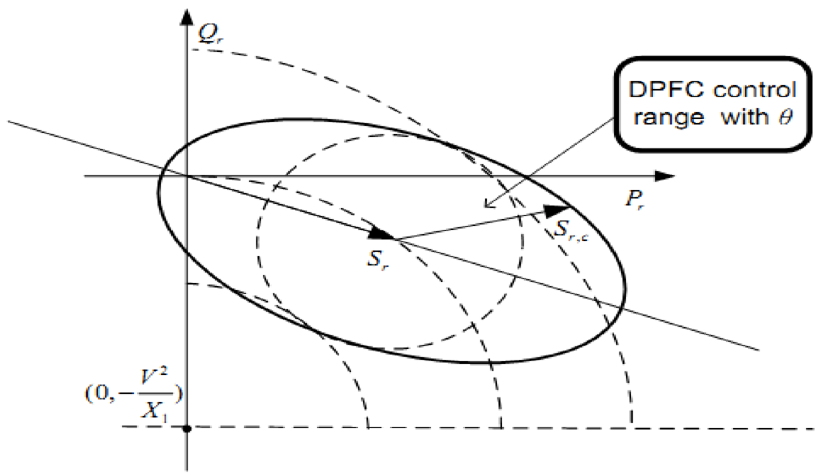


Figure 3-13: power flow control range of DPFC [19]

Chapter 4

DPFC MODELING AND BASIC CONTROL

4.1 INTRODUCTION

In the previous chapter, the new FACTS device, a DPFC, as well as its operating principle were introduced. To enable the control of the DPFC, controllers for individual DPFC converters are needed. This chapter addresses the basic control system of the DPFC, which is composed of shunt/series control that are highlighted in the Figure 4-1.

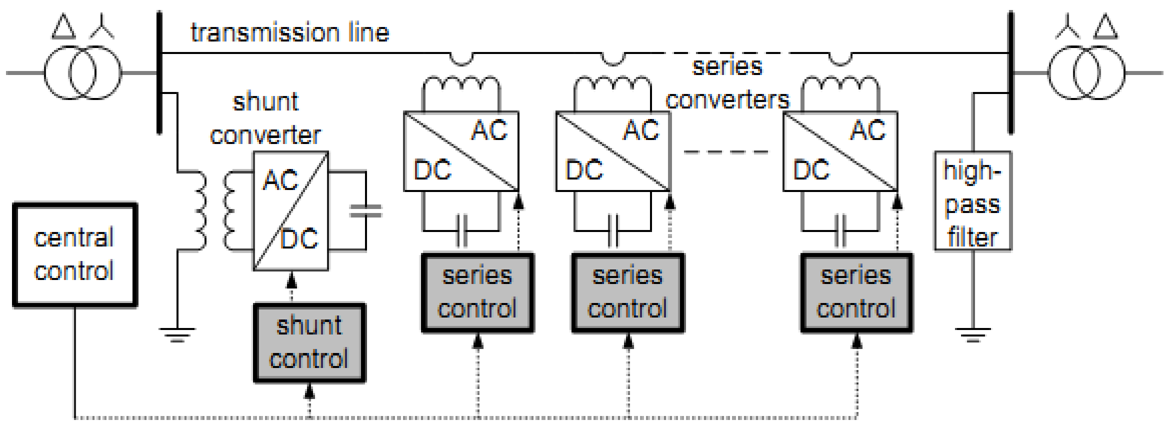


Figure 4-1: DPFC basic control [17]

The functions of the series control can be summarized as:

• It Maintain the capacitor DC voltage.

• Generate the series voltage at the fundamental frequency.

The functions of the shunt control are:

• 3^{rd} harmonic current should inject to supply active power for series converters.

• By absorbing active power from the grid at the fundamental frequency it maintain the capacitor DC voltage.

• Inject reactive voltage in the fundamental frequency to the grid as prescribed by the central control.

Firstly DPFC is modeled in d_q-frame. The AC components of the DPFC are transformed to DC components by using Park's (d_q) transformation. The transformed DC components of the DPFC can be controlled by traditional PI controllers. The basic control is responsible for maintaining the DC voltages of the DPFC converters and generating the AC voltages as prescribed by the central control [17, 19].

4.2 DPFC MODELING

To design a DPFC control scheme, the DPFC must first be modeled. This section presents such modeling of the DPFC. As the DPFC serves the power system, the model should explain the characteristics of the DPFC at the system level, which is at the fundamental and the 3rd harmonic frequency [21].

4.2.1 DPFC Model Overview

The modeling of the DPFC consists of the converter modeling and the network modeling. Due to the use of single-phase series converters, they are modeled as a single-phase system. To ensure that the single-phase series converter model is compatible with the three-phase network model, the network is modeled as three single-phase networks with 120◦ phase shift. Figure 4-2 gives the flow chart of the DPFC modeling process, which leads to six separated models.

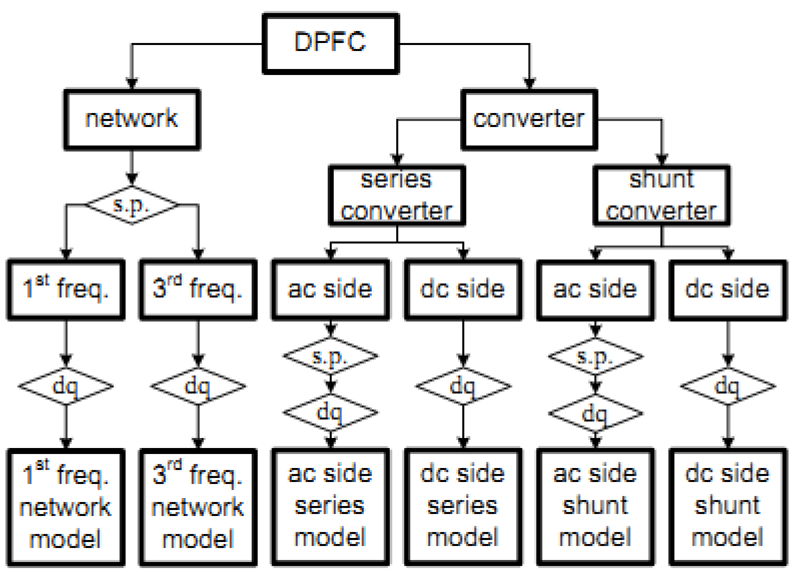


Figure 4-2: DPFC modeling process flow chat

Two tools are employed for the DPFC modeling: the superposition theorem and Park's transformation. As is well known, the transmission network is a linear system and the superposition theorem can therefore be applied. However, for the converter, certain approximations are needed for the application of the superposition theorem. Within the flow chart, the diamond shapes with 's.p.' indicate the process of applying the superposition theorem, and the shapes with 'd_q' represent the process of Park's transformation.

Because Park's transformation is designed for analysis of signals at a single frequency and the DPFC signal consists of two frequency components, the superposition theorem is first used to separate the components. Then, the component at different frequencies are subjected to Park's transformation and analyzed separately. Park's transformation, which is widely used in electrical machinery analysis, transforms AC components into DC. The principle of Park's transformation is to project the AC signal in vector representation on to a rotating reference frame, referred to as the 'd_q-frame'. The frequency of the rotation is chosen to be the same as the frequency of the AC signal. As a result, the voltages and the current in the d_q-reference are constant in steady-state.

The components at different frequencies are transformed into two independent rotating reference frames at different frequencies. The components at the fundamental frequency are 3-phase components, so Park's transformation can be applied directly. However, as Park's transformation is designed for a 3-phase system, a variation is required before its application to a single-phase system. The reason for this is that the 3rd harmonic component of a three phase system can be considered a single-phase component, as its components are all in phase ('zero-sequence'). A detailed description of single-phase Park's transformation discussed below.

4.2.2 Connection of Separated Models

The DPFC is modeled in separated parts. In this subsection, the connection between the models of separated parts is presented, as shown in Figure 4-3. As shown, the DPFC model consists of the fundamental frequency network model, the 3rd harmonic frequency network model, the series converter model and the shunt converter model. The fundamental frequency network model calculates the current through the line I_1 based on sending end, receiving end and series converter voltages. This current feeds back to the shunt and series converter models for the DC voltage calculation and to the central control for applications at the power system level. The 3rd harmonic frequency network model calculates the current I_3 from the voltages injected by the shunt and the series converters. The 3rd harmonic current is used for the calculation of the converter's DC voltages and it is also one of the control objects of the shunt control.

4.2.3 Network Modeling

This section presents the mathematical representation of a network with a DPFC at both the fundamental and the 3^{rd} harmonic frequencies. As the circuits at the two frequencies have been separated by the superposition theorem, the modeling of each circuit is presented separately.

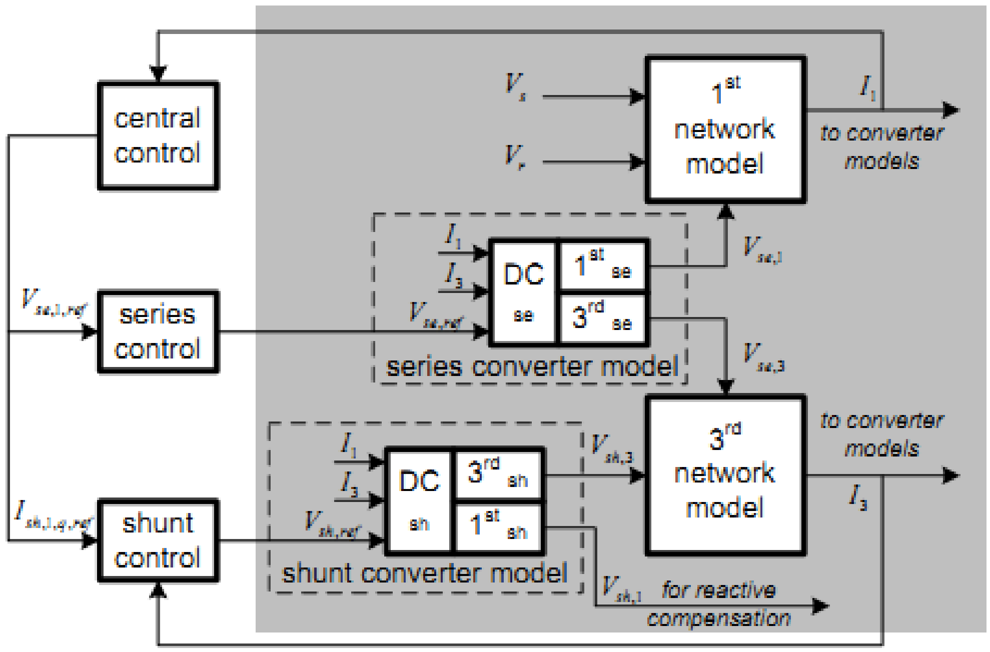


Figure 4-3: Connection of the separated models of the DPFC

Fundamental frequency network modeling

During the process of the network modeling, the DPFC converters can be considered controllable voltage sources. In a practical transmission system, perfect balance between phases is often assumed because the effect of the asymmetry is usually small, especially if the lines are transposed along their lengths. Most overhead transmission lines have at least two overhead conductors called ground wires, which are grounded at uniform intervals along the length of the lines. Therefore, the grounding can be treated as an ideal conductor with zero impedance and the mutual impedances between phases can be neglected.

With these assumptions, the network with the DPFC series converters at the fundamental frequency can be simplified as shown in Figure 4-4. With the equivalent circuit, the voltages at the fundamental frequency injected by the series converters is $V_{se,1}$, the line impedance is Z_1, and the voltages at the sending and receiving ends are V_r and V_s, respectively. The voltages $V_{se,1}$, V_r, V_s and the current I_1 are column vectors, which consist of information for the three phases. At the fundamental frequency, the network is modeled as three single-phase systems whose phases are shifted by 120◦

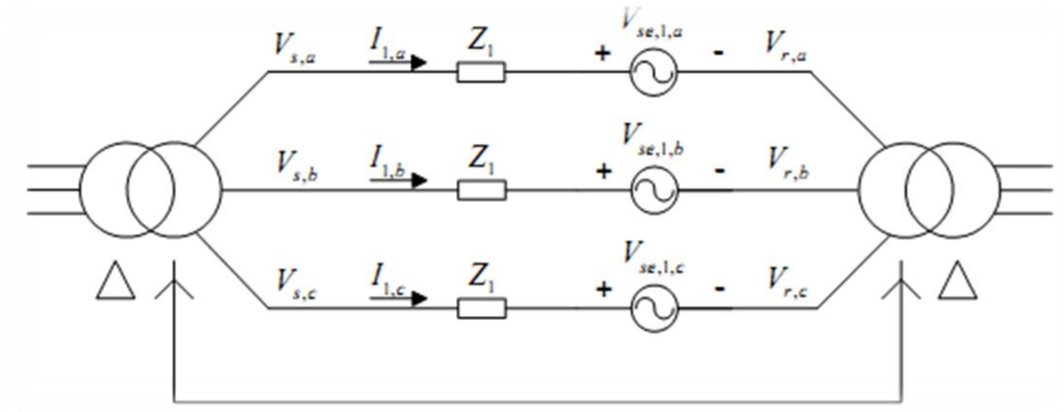


Figure 4-4: Fundamental frequency network equivalent circuit

According to the equivalent circuit, the relationship between the line current I_1 and the series voltage is given by:

$$\begin{bmatrix} V_{s,a} \\ V_{s,b} \\ V_{s,c} \end{bmatrix} - \begin{bmatrix} V_{r,a} \\ V_{r,b} \\ V_{r,c} \end{bmatrix} - \begin{bmatrix} V_{se,1,a,} \\ V_{se,1,b} \\ V_{se,1,c} \end{bmatrix} = \begin{bmatrix} Z_1 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_1 \end{bmatrix} \begin{bmatrix} i_{1,a} \\ i_{1,b} \\ i_{1,c} \end{bmatrix} \tag{4.1}$$

The model of the DPFC fundamental frequency represents how DPFC series converters affect the current through the transmission line by varying the injected voltages. Accordingly, the input of the model is the voltage injected by the series converters $V_{se,1}$, and the output is the line current I_1. The voltage at the sending and the receiving ends can be considered constant in the two-port network. While for the meshed network modeling, these two voltages can also be treated as the inputs [2, 17]. A block diagram of the fundamental network model is shown in Figure 4-5.

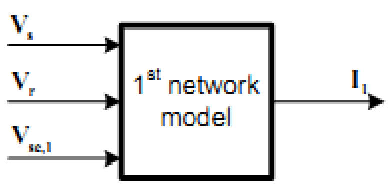


Figure 4-5: Input and output of the fundamental frequency network model

Third harmonic frequency network modeling

Within the DPFC, the shunt converter injects 3rd harmonic current at the neutral point of the Y-Δ transformer, as shown in Figure 3-7. This current distributes over the three phases and makes a closed-loop through the grounded neutral point of the other Y-Δ transformer. By representing the converters with voltage sources, the equivalent circuit for the 3rd harmonic frequency network can be simplified as shown in Figure 4-6.

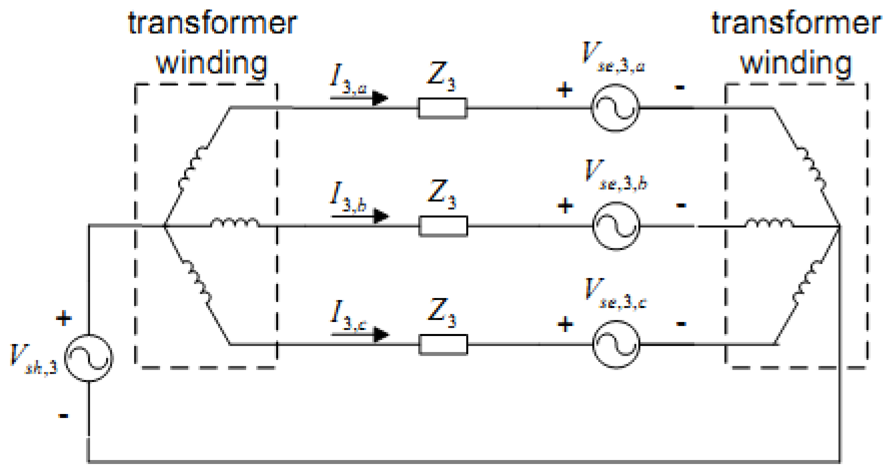


Figure 4-6: 3rd harmonic network equivalent circuit

The zero sequence reactance of the two transformer windings and the line impedance can be combined. This total impedance at the 3rd harmonic frequency is represented by Z_3. As described before, the neutral impedance is assumed to be zero. Therefore, the relationship between the voltages and the currents at the 3rd harmonic frequency is:

$$\begin{bmatrix} V_{sh,3} - V_{se,3,a} \\ V_{sh,3} - V_{se,3,b} \\ V_{sh,3} - V_{se,3,c} \end{bmatrix} = \begin{bmatrix} Z_3 & 0 & 0 \\ 0 & Z_3 & 0 \\ 0 & 0 & Z_3 \end{bmatrix} \begin{bmatrix} I_{3,a} \\ I_{3,b} \\ I_{3,c} \end{bmatrix} \tag{4.2}$$

The 3rd harmonic network model represents the 3rd harmonic current within each phase, which is caused by the 3rd harmonic voltage injected by the shunt and the series DPFC converters. The inputs of the model are the voltages V_{sh3} and $V_{se,3}$, which come from the converter models, while the output of the model is the 3rd harmonic current of each phase I_3, as shown in Figure 4-7.

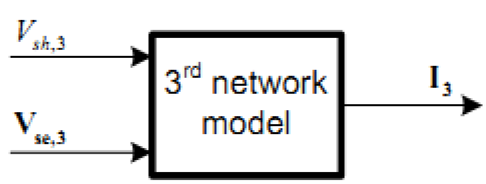


Figure 4-7: Input and output of the 3rd harmonic frequency network model

4.2.4 Series Converter Modeling

The DPFC series converters are identical, as are their models. The series converter is PWM control single-phase converter. Its simplified configuration is shown in Figure 4-8. As mentioned before, the switching behavior of the converter is not considered. To simplify the analysis, the loss of the converter is neglected.

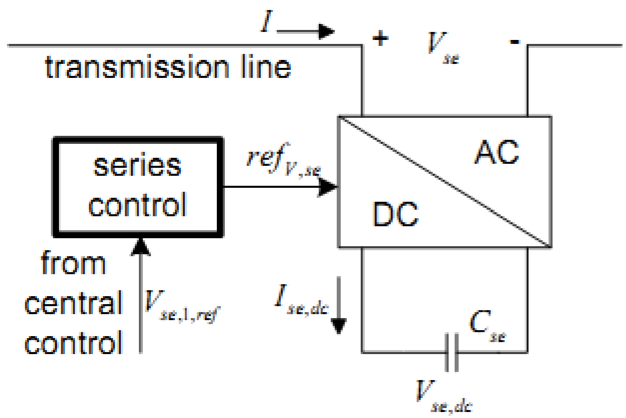


Figure 4-8: Simplified diagram of a series converter

Due to the identity of the series converters, Figure 4-8 depicts a converter that is availed in all three phases. To distinguish the converter in different phases, a subscript of phase could be added to the voltages and currents in Figure 4-8 if necessary. The AC side and the DC side voltages of the series converter are V_{se} and $V_{se,DC}$ respectively and " ref $_{v,se}$" the modulation amplitude of the reference AC signal in 'pu', which is generated by the series control. Note that the AC voltages and currents in Figure 4-8 consist of two components at different frequencies, namely the fundamental and the 3rd harmonic frequency components that are denoted by subscripts '1' and '3' respectively [1, 2]. Their relationship can be illustrated as follows:

$$V_{se} = V_{se,1} + V_{se,3} \tag{4.3}$$

AC side modeling

The series converter is a PWM converter. The AC side voltage of the converter can be approximated with the product of the AC reference signal and the DC voltage as V_{se}:

$$V_{se} = ref_{V,se} . V_{se,dc} \tag{4.4}$$

The reference signal is 'pu' value with the range from -1 to 1. By applying the super position theorem to the equation, equation (4.4) can be separated into: The input signals of the AC side model of the series converter is $ref_{v,se}$ and $V_{se,dc}$ and the output is the AC voltage V_{se}, which comes from the DC side model.

The reference signal is 'pu' value with the range from -1 to 1. By applying the superposition theorem to the equation, equation (4.4) can be separated into:

$$\begin{bmatrix} V_{se,1} \\ V_{se,3} \end{bmatrix} = \begin{bmatrix} refv_{se,1} \\ refv_{se,3} \end{bmatrix} V_{se,dc} \quad (4.5)$$

The input signals of the AC side model of the series converter is ref $_{v,se}$ and $V_{se,dc}$ and the output is the AC voltage V_{se}, which comes from the DC side model.

DC side modeling

The DC voltage of the series converter $V_{dc,se}$ is related with the DC current $I_{dc,se}$ and the relationship is given by:

$$Cse\frac{dVdc,se}{dt} = Idc,se \quad (4.6)$$

Two frequency components exist in both the reference voltage and the AC current. The DC side current of the series converter is approximated to:

$$\mathrm{Idc,se} = \mathrm{refv,se\,.\,I} = (\mathrm{refv,se,1} + \mathrm{refv,se,3})(\mathrm{I1} + \mathrm{I3}) \quad (4.7)$$

and the DC voltage can be written as:

$$Cse\frac{dVdc,se}{dt} = (\mathrm{refv,se,1} + \mathrm{refv,se,3})(\mathrm{I1} + \mathrm{I3}) \quad (4.8)$$

By applying the inverse single-phase Park's transformation, explained in Appendix A, we obtain:

$$Cse\frac{dVdc,se}{dt} = \mathrm{refv,se,1,d}\sin\theta + \mathrm{refv,se,1,q}\cos\theta + \mathrm{refv,se,3,d}\sin 3\theta + \mathrm{refv,se,3,q}\cos 3\theta)(\mathrm{I1,d}\sin\theta + \mathrm{I1,q}\cos\theta + \mathrm{I3,d}\sin 3\theta + \mathrm{I3,q}\cos 3\theta) \quad (4.9)$$

where θ is the angle of the rotation reference frame for Park's transformation. On the right side of (4.9), there are cross terms of different frequency components, which appear as zero-average ripples superimposed with the DC voltage. As this ripple has no contribution to the DC voltage magnitude, the terms that cause the ripple are neglected during the modeling. Therefore, the DC voltage can be approximated to:

$$Cse\frac{dVdc,se}{dt} = \frac{1}{2}((\mathrm{refv,se,1,dI1,d} + \mathrm{refv,se,1,qI1,q}) + \frac{1}{2}(\mathrm{refv,se,3,dI3,d} + \mathrm{refv,se,3,qI3,q}) \quad (4.10)$$

DC side modeling

The DC voltage of the series converter $V_{dc,se}$ is related with the DC current $I_{dc,se}$ and the relationship is given by:

$$Cse \frac{dVdc,se}{dt} = \mathrm{Idc,se} \tag{4.11}$$

Two frequency components exist in both the reference voltage and the AC current. The DC side current of the series converter is approximated to:

$$\mathrm{Idc,se} = \mathrm{refv,se\ I} = (\mathrm{refv,se,1} + \mathrm{refv,se,3})(\mathrm{I1} + \mathrm{I3}) \tag{4.12}$$

and the DC voltage can be written as:

$$Cse \frac{dVdc,se}{dt} = (\mathrm{refv,se,1} + \mathrm{refv,se,3})(\mathrm{I1} + \mathrm{I3}) \tag{4.13}$$

By applying the inverse single-phase Park's transformation, we

obtain: C_{se} $dVd_{c,se}$ dt

$$\begin{aligned} C_{se} \frac{dV_{dc,se}}{dt} = (&ref v_{se,1,d} \sin\theta \\ &+ ref v_{se,1,q} \cos\theta \\ &+ ref v_{se,3,d} \sin 3\theta \\ &+ ref v_{se,3,q} \cos 3\theta).(I_{1,d} \sin\theta + I_{1,q} \cos\theta + I_{3,d} \sin 3\theta + I_{3,q} \cos 3\theta \end{aligned} \tag{4.14}$$

where θ is the angle of the rotation reference frame for Park's transformation. On the right side of (4.14), there are cross terms of different frequency components, which appear as zero-average ripples superimposed with the DC voltage. As this ripple has no contribution to the DC voltage magnitude, the terms that cause the ripple are neglected during the modeling. Therefore, the DC voltage can be approximated to:

$$\begin{aligned} C_{se} \frac{dV_{dc,se}}{dt} = \frac{1}{2}\left(ref v_{se,1,d}.I_{1,d} + ref v_{se,1,q}.I_{1,q}\right) + \frac{1}{2}(&ref v_{se,3,d}.I_{3,d} \\ &+ ref v_{se,3,q}.I_{3,q}) \end{aligned} \tag{4.15}$$

Accordingly, the input signals for the DC side model are $ref_{v,se,1}$, $ref_{v,se,3}$, I_1 and I_3, and the output is the DC voltage $V_{se,dc}$. Equation (4.14) can accurately represent the series convertor capacitor

DC voltage, which consists of the mean-value and the ripple, while equation (4.15) neglects the ripple. During the design of the DPFC, the capacitance of the series converter is selected to limit the ripple within a 5% error of the nominal DC voltage. Therefore, the model given in (4.15) is sufficiently accurate for the DC voltage calculation.

Series converter model

By combining the models of the AC side and the DC side, the series converter model is shown in Figure 4-9.

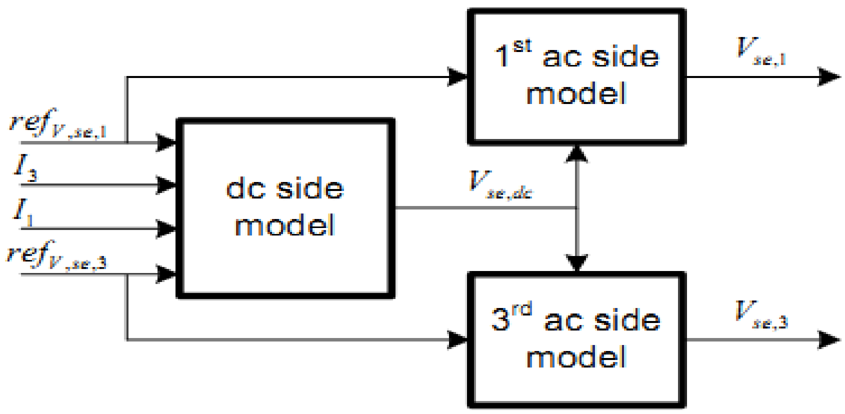


Figure 4-9: Block diagram of the series converter model

The input signals for the series converter model are the reference voltage from the series control and the line current, taken at both frequencies. The output signal of the model is the AC voltage generated by the series converter.

4.2.5 Shunt Converter Modeling

The shunt converter consists of a 3-Φ converter that is back-to-back connected to a 1-Φ converter. Similar as a STATCOM, the three-phase converter is connected to the low voltage side of the Y-Δ transformer to absorb active power from the system. The single phase converter is connected between the ground and the neutral point of the Y-Δ transformer to inject 3rd harmonic current. The diagram for shunt converter is shown in Figure 4-10.

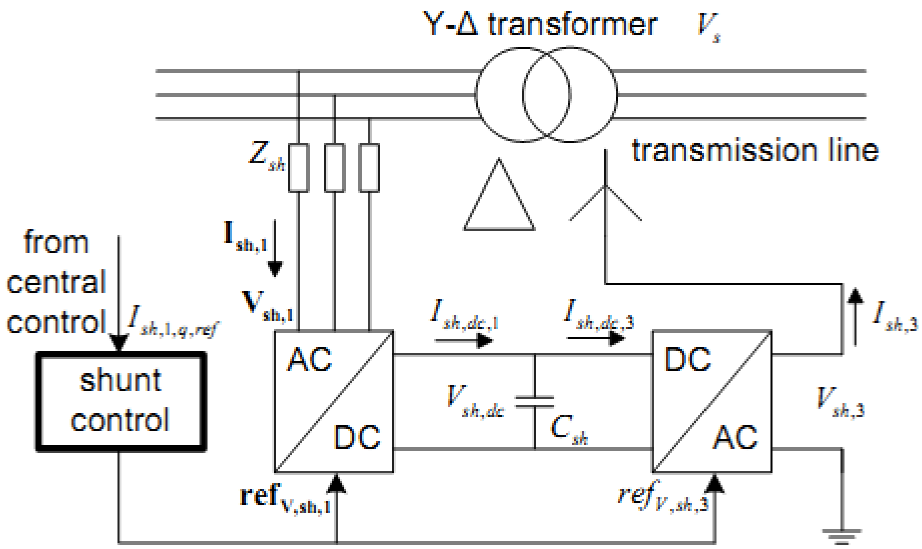


Figure 4-10: Simplified diagram of the shunt converter

Due to no 3rd harmonic component at the Δ side of the transformer, the converter at the left side contains only the components at the fundamental frequency, namely the voltage $V_{sh,1}$ and the current $I_{sh,1}$. The voltage $V_{sh,3}$ and current $I_{sh,3}$ at the 3rd harmonic frequency are single-phase components.

AC side modeling

Similar to the series converter modeling, the AC voltage can be approximately written as follows:

$$V_{sh,1} = refv_{sh,1}.V_{sh,dc}$$

$$V_{sh,3} = refv_{sh,3}.V_{sh,dc} \tag{4.16}$$

where the modulation amplitudes $ref_{v,sh,1}$ and $ref_{v,sh,3}$ are 'pu' values with the range from -1 to 1.

DC side modeling

The capacitor DC voltage of the shunt converter is given with the following equation:

$$C_{sh}\frac{dV_{sh,dc}}{dt} = I_{sh,dc,1} - I_{sh,dc} \tag{4.17}$$

By applying Park's transformation to the fundamental frequency components, the DC current at the three-phase side can be found:

$$I_{sh,dc,1} = \frac{3}{2}(refv_{sh,1,d}.I_{sh,1,d} + refv_{sh,1,q}.I_{sh,1,q}) \quad (4.18)$$

If the three-phase components are symmetrical, the DC current $I_{sh,dc,1}$ is a constant with no ripple. By substituting single-phase Park's transformation into the 3rd harmonic components, the 3rd DC current is:

$$I_{sh,dc,3} = (refv_{sh,3,d}\sin 3\theta + refv_{sh,3,q}\cos 3\theta)(I_{sh,3,d}\sin 3\theta + I_{sh,3,q}\cos 3\theta) \quad (4.19)$$

As previously discussed concerning series converter modeling, terms with zero-average values will not contribute to the capacitor DC voltage while appearing as ripples of the DC voltage. By neglecting these terms, the shunt converter DC voltage can be approximated by:

$$Csh\frac{dVsh,dc}{dt} = \frac{3}{2}(refv,sh,1,dIsh,1,d + refv,sh,1,qIsh,1,q)$$

$$-\frac{1}{2}(refv,sh,3,dIsh,3,d + refv,sh,3,qIsh,3,q) \quad (4.20)$$

Shunt converter model

The overall shunt converter model, created by connecting the AC and DC sides of the shunt converter model, is shown in Figure 4-11.

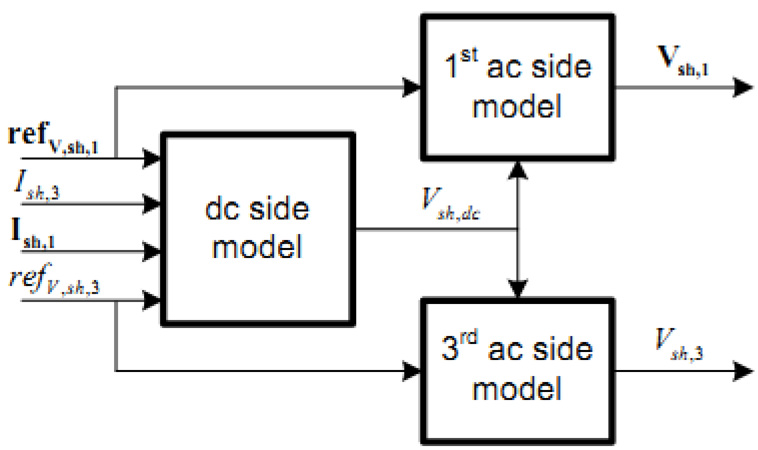


Figure 4-11: Block diagram of the series converter model

The input signals for the model are reference voltage signals and current, at both frequencies, while the outputs are the fundamental and 3rd harmonic frequency voltages, generated by the shunt converter.

4.3 DPFC BASIC CONTROL

Based on the DPFC model presented previously, the control can now be further developed. The DPFC basic control consists of the series control and the shunt control. In this section, the control schemes and their corresponding design are addressed. Because of its simple implementation, the vector control method is employed to control the DPFC converter. The calculation of the controller parameter is based on the Internal Model Control (IMC) method.

4.3.1 Series converter control

DPFC series converter is controlled by its own controller, and it is an identical scheme for control purpose. To control the series converter, independent control loops are used for the two frequency components. The 3rd harmonic control loop is used to control DC voltage [19]. The block diagram of the series converter control DPFC shown in Figure 4-12

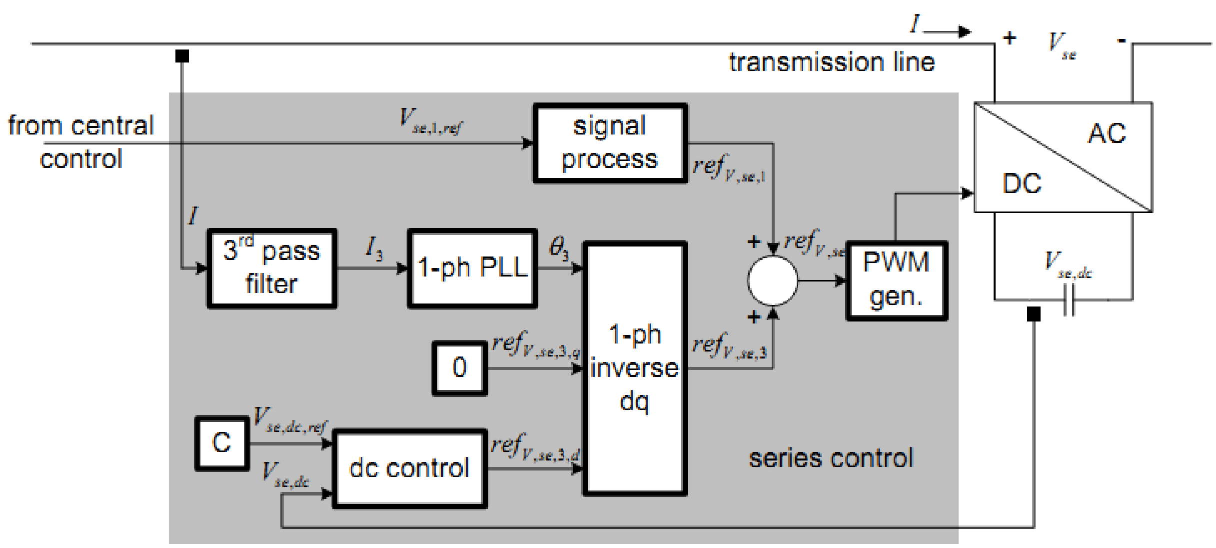


Figure 4-12: Control scheme of the series converter [19]

Third harmonic frequency component control as shown in Figure 4-12, the 3rd harmonic frequency control is the major control loop in the DPFC series converter control. Its main work is to maintain the DC capacitor voltage. Vector control principle is used here for DC voltage control. Normally, the voltage is used as the rotation reference frame for Park's transformation, principle.

As the current line contains two frequency components, one filter passband is required to extract the 3rd harmonic current. The single phase Phase-Lock-Loop (PLL), as described hereinafter, creates a frame of reference rotating the 3rd harmonic current. The d-component of the 3rd harmonic voltage is the parameter used to control the DC voltage. The control signal is generated by the control loop DC voltage. Because the q-component of the third harmonic voltage only cause the injection of reactive power to the AC network, the q-component is held at zero during the operation [17, 19]

DC voltage control design

The DC voltage control loop is used for maintaining the DC voltage of the series converter. Within the series converter control, both frequency component currents are taken as their rotating reference frame for Park's transformation. By projecting the currents to themselves, the q-components $I_{1,q}$ and $I_{3,q}$ that are perpendicular to the current, will be zero and (4.15) can be written as:

$$Cse\frac{dVse,dc}{dt} = \frac{1}{2}(refv,se,1,dI1,d\ +\ refv,se,3,dI3,d) \quad (4.21)$$

As shown, the DC capacitor voltage is affected by both the fundamental and the 3rd harmonic frequency components. The components at the fundamental frequency $ref_{v,se,1,d}$, $I_{1,d}$ can be treated as a disturbance. Because the 3rd harmonic current within the line is a constant value, the current $I_{3,d}$ is considered constant.

To design the controller, the time-domain to the frequency domain (s-domain) using the Laplace Transform. By selecting $ref_{v,se,3,d}$ as the control parameter and $V_{se,dc}$ as the control object, the transfer function from $ref_{v,se,3,d}$ to $V_{se,dc}$ is found:

$$G(s)\ =\ \frac{Vse,dc(s)}{refv,se,3,d(s)} = \frac{I3,d}{2Cse,s} \quad (4.22)$$

As shown, the pole of the transfer function is at the origin. To improve disturbance rejection, an inner feedback loop is introduced for active damping as a part of the DC voltage control loop. DC voltage control scheme is shown in Figure 4-13.

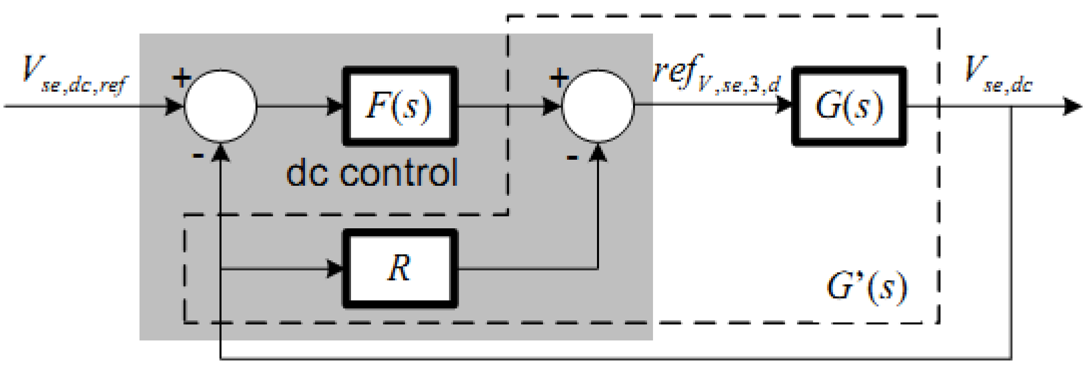


Figure 4-13: Scheme of DC voltage control loop of the series converter

Within the DC control, F(s) is the control function and 'R' is the active damping taken as feedback in the controller. The active damping and G(s) results in a new virtual system G′(s). The transfer function of G′(s) is given by:

$$G'(s) = \frac{G(s)}{\left(1 + RG(s)\right)} = \frac{I_{3,d}}{2sC_{se} + RI_{3,d}} \tag{4.23}$$

The virtual system G′(s) is a first order system and according to the IMC method, the control function for a first order system is given by:

$$F(s) = \frac{\alpha d}{s} G'(s)^{-1} \tag{4.24}$$

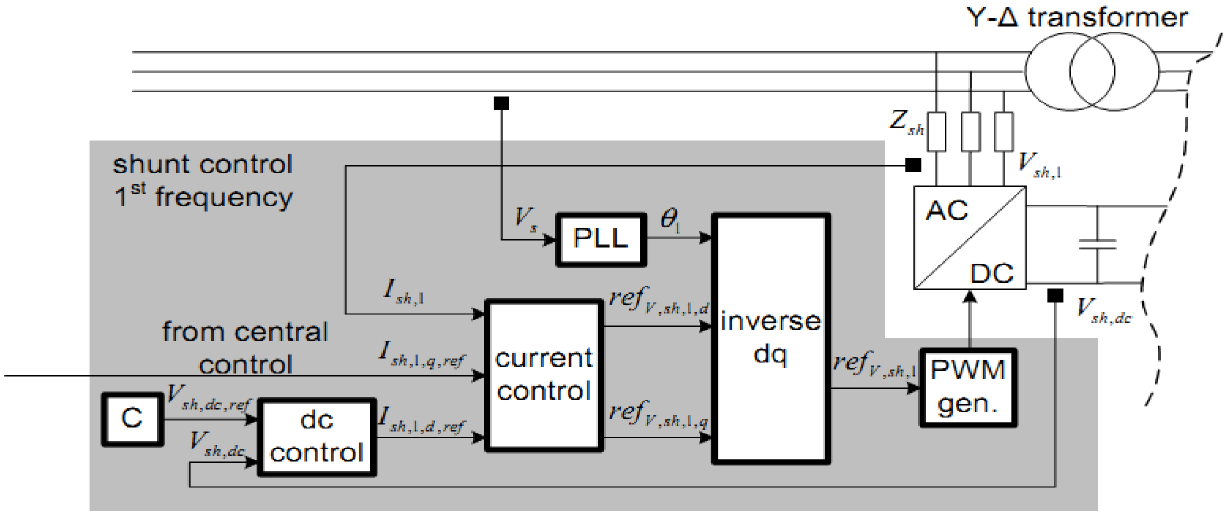
where αd is a design parameter, The relation between the bandwidth and the rise time tries (from 10% to 90% of the final value) is:

$$\alpha_d = \frac{ln\, 9}{t_{rise}} \tag{4.24}$$

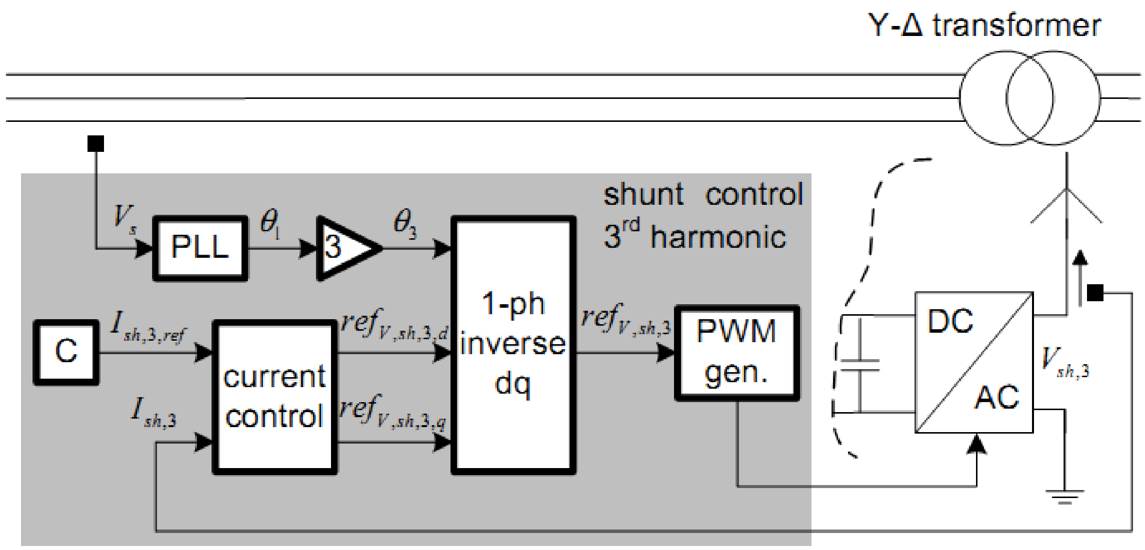
4.3.2 Shunt converter control

The shunt converter having two converters as shown in Figure 4-10 . The single phase converter injects the 3rd harmonic constant current into the network. The three phase converter maintains the DC voltage at a fix value and generates reactive power to the network. The control of each converter is independent. A block diagram of the shunt converter control is shown in Figure 4-14.

Control of the third harmonic frequency component the converter that is connected between the neutral point of the Y-Δ transformer and the ground is a single phase converter. It is responsible for injecting a constant 3rd harmonic current into the network, therefore requiring a current controller. The 3rd harmonic current is locked with the bus voltage at the fundamental frequency. A PLL is using to capture the bus voltage frequency, and the output signal of the PLL θ_1 is modified by 3 times to create a virtual rotation reference frame for the 3rd harmonic component [25].



(a)



(b)

Figure 4-14: shunt converter control scheme: (a) fundamental frequency components [25]; (b) shows the 3rd harmonic frequency components [25]

Current control design:

The current control loop is the major loop within the shunt converter's 3rd harmonic control. In order to design the current control, the relationship between the 3rd harmonic current and the shunt voltage should be determined. Assuming that the DC voltage of the back-to-back converter is constant, the shunt and series converters can be represented by voltage sources. From Figure 4-7, the 3rd harmonic circuit can be further simplified into two voltage sources series connected to an inductor and resistor, as shown in Figure 4-15.

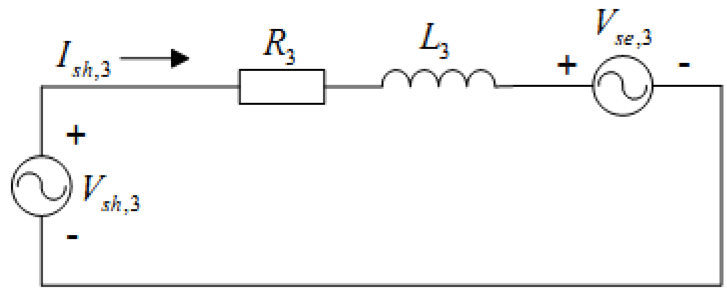


Figure 4-15: Simplified 3rd harmonic circuit

The resistor R_3 and L_3 are the equivalent resistance and inductance of the network at the 3rd harmonic frequency. The circuit shows relationship between current and voltage as given below:

$$V_{sh,3} = L_3 \frac{dI_{sh,3}}{dt} + R_3 I_{sh,3} + V_{se,3} \tag{4.25}$$

By applying Park's transformation to (4.24), the relationship between the voltage and the current in the dq-frame can be determined:

$$V_{sh,3,d} = R_3 I_{sh,3,d} + L_3 \frac{dI_{sh,3,d}}{dt} - \omega_3 L_3 I_{sh,3,q} + V_{se,3,d}$$

$$V_{sh,3,q} = R_3 I_{sh,3,q} + L_3 \frac{dI_{sh,3,q}}{dt} - \omega_3 L_3 I_{sh,3,d} + V_{se,3,q} \tag{4.26}$$

where ω_3 is the 3rd harmonic angular velocity. The terms with ω_3 in both equations cause a coupling of the two equations. To decouple the control of the 'd' and 'q' components, the coupling terms can be cross added with the signal generated by the PI controller. The voltage injected by series converter $V_{se,3}$ and the coupling terms within (4.26) can be considered disturbances. By transforming (4.26) into the frequency-domain, the transfer functions from the voltage $V_{sh,3}$ to the current $I_{sh,3}$ for both 'd' and 'q' components are the same and can be expressed as:

$$G(s) = \frac{1}{R_3 + sL_3} \tag{4.27}$$

As concerns the shunt converter, the injected voltage by the series converter is unpredictable. To minimize this disturbance, additional active damping is added as the inner feedback loop for each current control loop. Consequently, the scheme of the current control is shown in Figure 4-16.

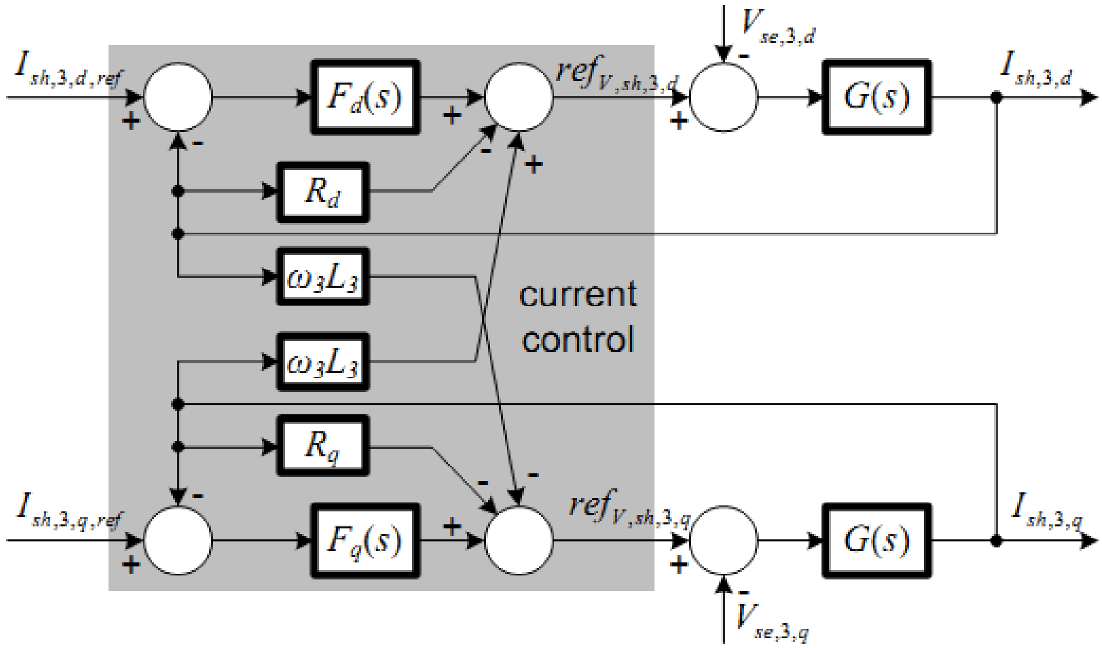


Figure 4-16: Scheme of the 3rd harmonic current control within the shunt converter

By using the IMC method, as introduced above, to design the current control, the parameters of the control functions F(s) can be calculated as:

$$F_d(s) = \alpha_d L_3 + \frac{\alpha_d (R_3 + R_d)}{s}$$

$$F_q(s) = \alpha_q L_3 + \frac{\alpha_q (R_3 + R_q)}{s} \tag{4.27}$$

where α_d and α_q are the bandwidths for the d and q components respectively, and the reactive damping R is given by:

$$R_d = \alpha_d L_3 - R_3$$

$$R_q = \alpha_q L_3 - R_3 \tag{4.28}$$

Control of the fundamental frequency component

The control of the shunt converter at the purpose of fundamental frequency is to inject a controllable reactive current into the grid and maintain the constant DC voltage of the capacitor. As shown in Figure 4-14, this control consists of two major blocks: the current control and the DC control. Inner control loop is the current controller, which controls the current $I_{sh,1}$. The reference of q-component of current is from the central control and the reference signal of the d-component is generated by the DC control. For Park's transformation, the rotation reference frame is created by the PLL using the bus voltage as input [11].

Current control design:

This control scheme is similar to the current control scheme for 3rd harmonic components. As the grid voltage V_s is available for the control, there is theoretically no disturbance of the system, and it is not necessary to add active damping for the control. The scheme of the current control is shown in Figure 4-17.

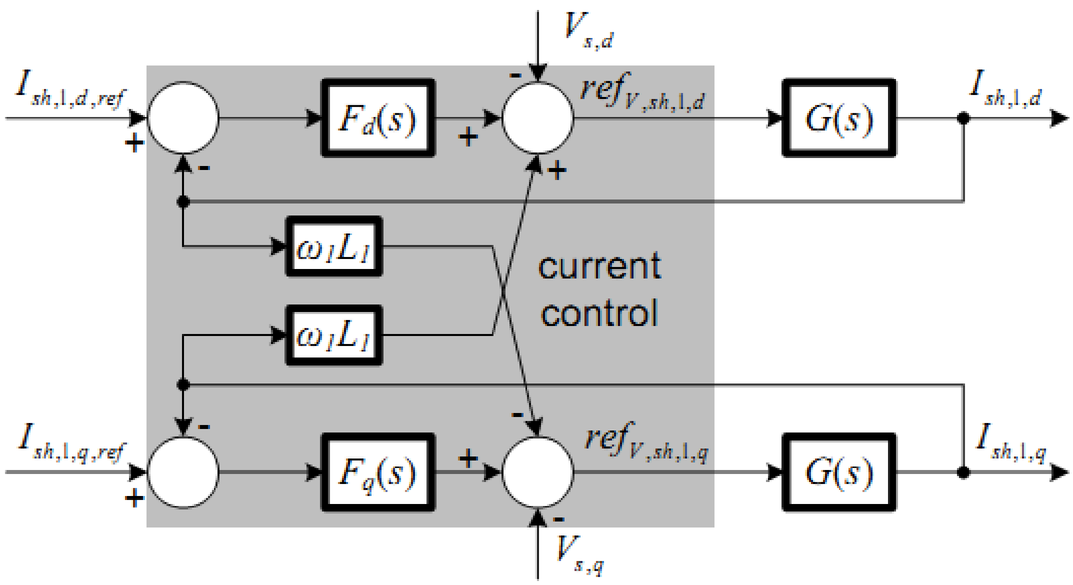


Figure 4-17: Scheme of the fundamental current control within the shunt converter

Within the scheme, ω_1 is the angular velocity of the system; L_1 and R_1 are equivalent to the inductance and resistance of the shunt converter at the fundamental frequency. This control is designed in the same way as the current control for 3rd harmonic components and the control function is given by:

$$F_d(s) = \alpha_d L_1 + \frac{\alpha_d R_1}{s}$$

$$F_q(s) = \alpha_q L_1 + \frac{\alpha_q R_1}{s} \tag{4.29}$$

DC control design

As presented in the section on the DPFC modeling at the beginning of this chapter, the DC voltage of the shunt converter is given as:

$$C_{se}\frac{dV_{dc,se}}{dt}=\frac{1}{2}(refv_{se,1,d}.I_{1,d}+refv_{se,1,q}.I_{1,q})+\frac{1}{2}(refv_{se,3,d}.refv_{se,3,q}+refv_{se,3,q}.I_{3,q})$$

(4.30)

For Park's transformation at the fundamental frequency, the rotation reference frame is derived from the bus voltage V_s. Neither the 'd' nor the 'q' component of the voltage $ref_{v,sh,1}$ is zero. Therefore, all the terms with $ref_{v,sh,1}$ have an influence on the DC voltage, which makes the control difficult. The DC voltage control of the shunt converter is based on another approach that treats the DC capacitor as an energy storage device. Neglecting losses, the time derivative of the stored energy equals the sum of instantaneous power at both frequencies;

$$\frac{1}{2}C_{sh}\frac{dV_{dc,sh}^2}{dt}=P_1-P_2 \quad (4.31)$$

Since the equation is nonlinear with respect to $V_{dc,sh}$, a new variable $W = V^2_{dc,sh}$ is introduced to overcome the nonlinearity. For the active calculation, because the resistance between the grid and the shunt converter is small, the active power is approximately the same at both ends. Within Park's transformation, the voltage V_s is the rotation reference frame. By projecting V_s to itself, the q-component of V_s is zero, and (4.31) can be written as:

$$\frac{1}{2}.C_{sh}\frac{dW}{dt}=\frac{3}{2}.V_{s,d}.I_{sh,1,d}-P_1 \quad (4.32)$$

The grid voltage V_s is constant and P_3 is considered a disturbance. By applying the Laplace transform, the transfer function from $I_{sh,1,d}$ to W is found as:

$$G(s)=\frac{W(s)}{I_{sh,1,d}(s)}=\frac{V_{s,d}}{sC_{sh}} \quad (4.33)$$

Similarly to the DC voltage control of the series converter, an inner feedback loop is also added for damping the pole at the origin [25]. A scheme of the DC voltage control of the shunt converter is shown in 4-18.

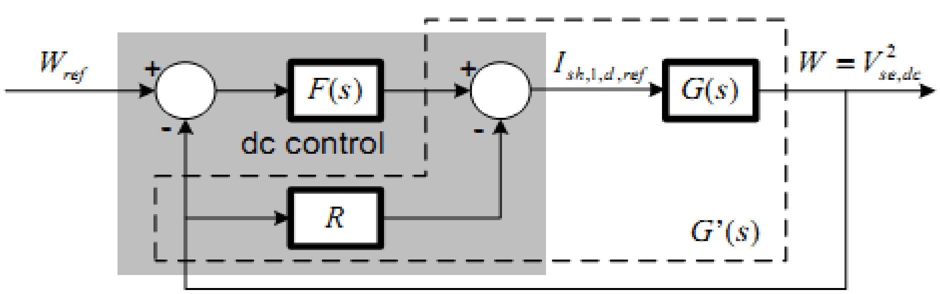


Figure 4-18: Scheme of the DC voltage control of the shunt converter

By using the IMC method, the control function and the active damping R can be calculated as:

$$R = \frac{\alpha C}{3v_{s,d}},\ K_p = \frac{\alpha C}{3v_{s,d}}, K_i = \frac{\alpha^2 C}{3v_{s,d}}, \tag{4.34}$$

4.3.3 Park's transformation

3-Phase Park's Transformation

The Park's transformation that is from abc-frame to dq0-frame is given by:

$$[x_{dq0}] = [T_{dq0}(\theta)].[x_{abc}] \tag{4.35}$$

where $[x_{dq0}]$ and $[x_{abc}]$ are vectors in different domains,

$$[x_{dq0}] = \begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix}, [x_{abc}] = \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{4.36}$$

and the transformation matrix $[T_{dq0(\theta)}]$ is given by:

$$[T_{dq0}] = \frac{1}{2}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\sin\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{4.37}$$

with '$\theta = \omega t + \phi$', where ω is the angular velocity, t is the time and ϕ is the initial angle. The factor 2/3 in $[T_{dq0(\theta)}]$ keeps the amplitude invariant, implying that the vectors of voltage and current in both abc-frame and dq0-frame have the same length. The inverse of $[T_{dq0(\theta)}]$ is given by:

$$[T_{dq0}]^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\sin\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \tag{4.38}$$

The factor 3/2 can simply be explained because the amplitude invariant Park's transformation converts 3-phase to 2-phase where vectors have the same amplitude in both domains. Therefore, the power in one phase is missing after the transformation. The factor 3/2 corrects this missing power [2].

Single-phase Park's Transformation

The Park's transformation is designed for 3-phase system. For single-phase system, variations are needed. Two single-phase Park's transformation methods have been proposed. The method, which creates a αβ-frame by delaying the single-phase signal by π/2, is employed here, because it is easy to be implemented.

With this method, a virtual two-phase system (αβ system) is created from the single-phase signal. The signal is the original input signal x and the β signal is created by applying a π/2 transport delay to x, as shown in Figure. As the α-axis is leading β-axis by π/2, the delayed signal is the minus of the β-axis.

The transformation from the stationary αβ-frame to rotating dq-frame is given by:

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{bmatrix} . \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \tag{4.39}$$

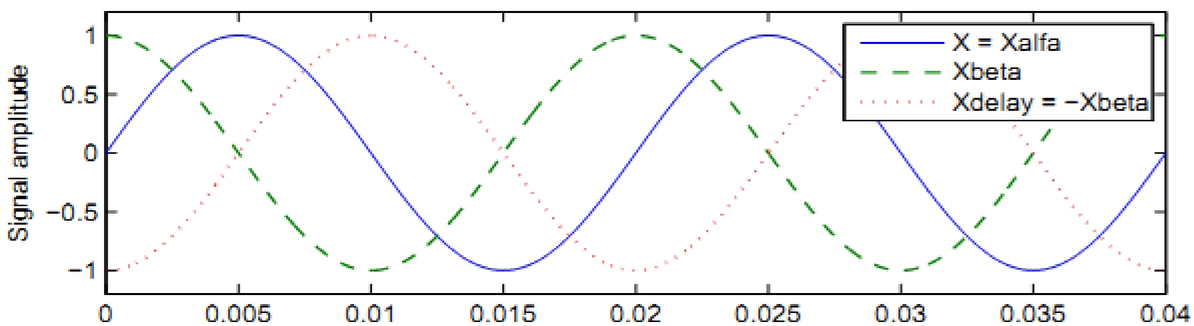


Figure 4-19 Relationship between x, $x_{\alpha\beta}$, and x_{delay}

The inverse single-phase transformation is from $[x_{dq}]$ to the single-phase signal x and is given by:

$$x = [\sin\theta \quad \cos\theta].[x_{dq}] \tag{4.40}$$

Components in the β-axis have the same amplitude as in the α-axis, so the power in single-phase frame is half of the power in αβ-frame. The single-phase power in dq-frame is given by:

$$S(t) = v(t).i(t) = \frac{1}{2}[v_{\alpha\beta}]^T.[i_{\alpha\beta}]$$

$$= \frac{1}{2}\left[[T_{\alpha\beta-dq}]^{-1}.[v_{dq}]\right]^T [T_{\alpha\beta-dq}]^{-1}[i_{dq}]$$

$$= \frac{1}{2}[v_{dq}]^T[T_{\alpha\beta-dq}][T_{\alpha\beta-dq}]^{-1}[i_{dq}]$$

$$= \frac{1}{2}\left[v_{dq}\right]^T\left[i_{dq}\right] \tag{4.41}$$

Note that in both 3-phase and single-phase dq-transformation, the length of the vector $x_d + jx_q$ is equals to the amplitude of vector x, but not the RMS value [1, 2]. For the phasor x =$\sqrt{2}X_{RMS}$ sin ωt, the length is:

$$\sqrt{x_d^2 + x_q^2} = \sqrt{2}X_{RMS} \tag{4.42}$$

4.3.4 Single-phase phase lock loop

Single-phase PLL plays an important role within the DPFC control. The topology of the PLL employed in the DPFC as shown below in Figure 4-20.

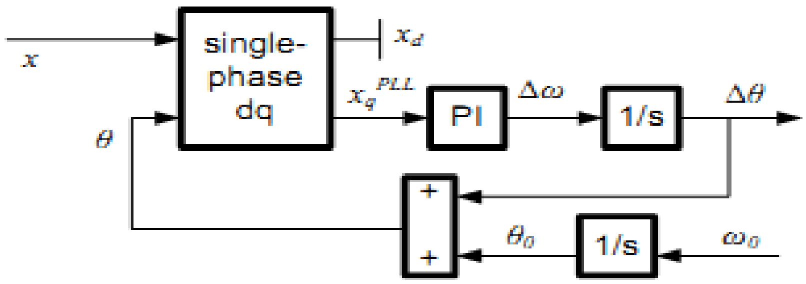


Figure 4-20: Topology of the single-phase PLL [2]

In the figure, 'x' is the input signal in AC quantity and 'θ' is the frequency and phase information where

$$\theta = \int_0^t \omega dt + \varphi \tag{4.43}$$

The symbol 'ω' is the angular frequency and 'ϕ' is the phase angle.

The single-phase PLL is based on the Park's transformation. If a phasor is projected to itself, its q-component will be zero. A rotated phasor is created, whose rotation frequency is obtained from the q-component of the input signal. A P-I controller is used to force the phase created by the PLL to approach the input signal. When the q-component x_q^{PLL} is zero, the PLL output is locked with input signal [11].

$$x_q^{PLL} = \sin(\omega t + \varphi).\cos(\omega t + \varphi_{PLL}) + \sin\left[(\omega t - \frac{\pi}{4}) + \varphi\right].\sin(\omega t + \varphi_{PLL})$$

$$= \sin(\varphi - \varphi_{PLL}) \tag{4.44}$$

To analyze the PLL, the phase angle 'ϕ' of the input AC signal is selected as the PLL input and ϕ^{PLL} is the output of the PLL. According to above equation the PLL can be represented by a single-input-single-output system as shown in Figure 4-21.

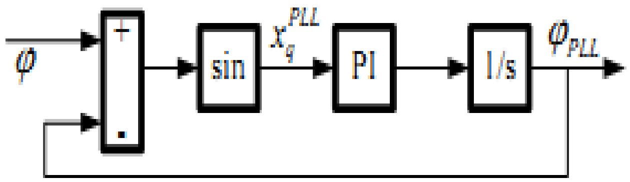


Figure 4-21: PLL representation by using phase angles as the input and output

Because difference between ϕ and ϕ^{PLL} is having small value, so the sinusoidal function in the PLL should be linearized as sinx = x for simplification. Consequently, by applying Laplace Transformation, The transfer-function (open-loop) of ϕ and ϕ_{PLL} can be written as:

$$G(s) = \left(\frac{K_i}{s} + K_p\right).\frac{1}{s} = \frac{K_i + sK_p}{s^2} \tag{4.45}$$

Then, the close-loop transfer function of the PLL is:

$$\frac{\varphi_{PLL}}{\varphi} = \frac{G(s)}{1 + G(s)}$$

$$= \frac{sK_p + K_i}{s^2 + sK_p + K_i} \tag{4.46}$$

As shown, the input and output of the PLL, same as the steady-state value. However, there is difference during transients and this difference depends on the parameters of PLL.

Chapter-5

SIMULATION & RESULTS OF THE DPFC MODELING

5.1 POWER FLOW CONTROL USING DPFC

Figure below shows the simulation diagram of power flow control using DFPC. This simulation diagram is the complete simulation diagram with system, sub-system and measurement blocks.

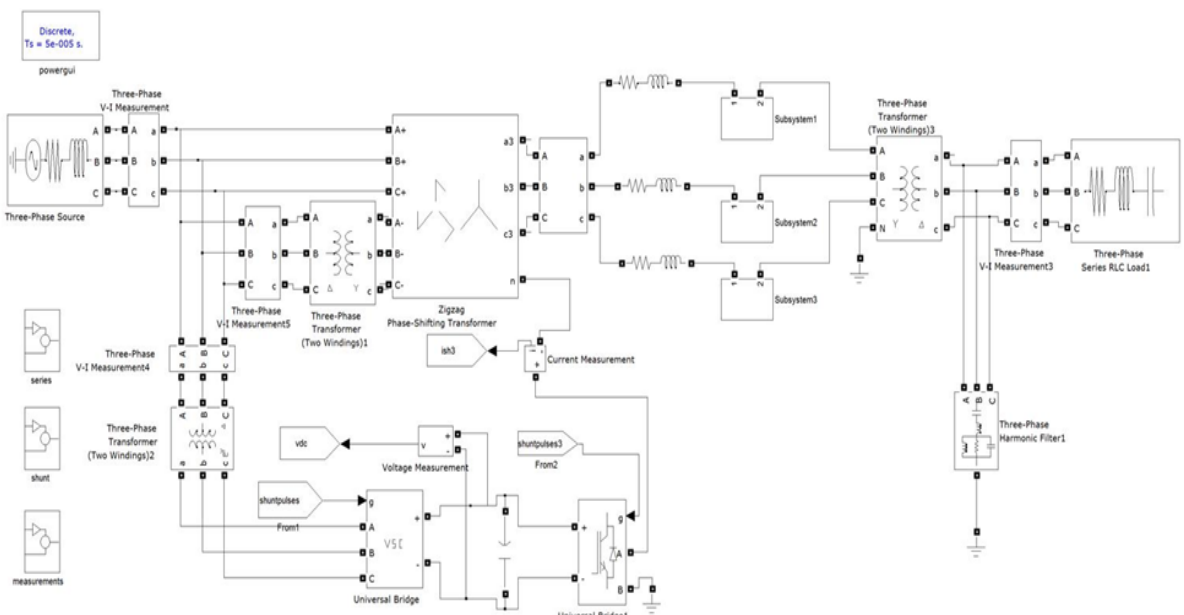


Figure 5-1 DPFC Simulink modeling

5.1.1 Sub system

Sub system is the system in which we are incorporate many of the blocks (to introduce inputs and reference voltages & currents to the main system) internally to show our main system/simulink clean and clear view.

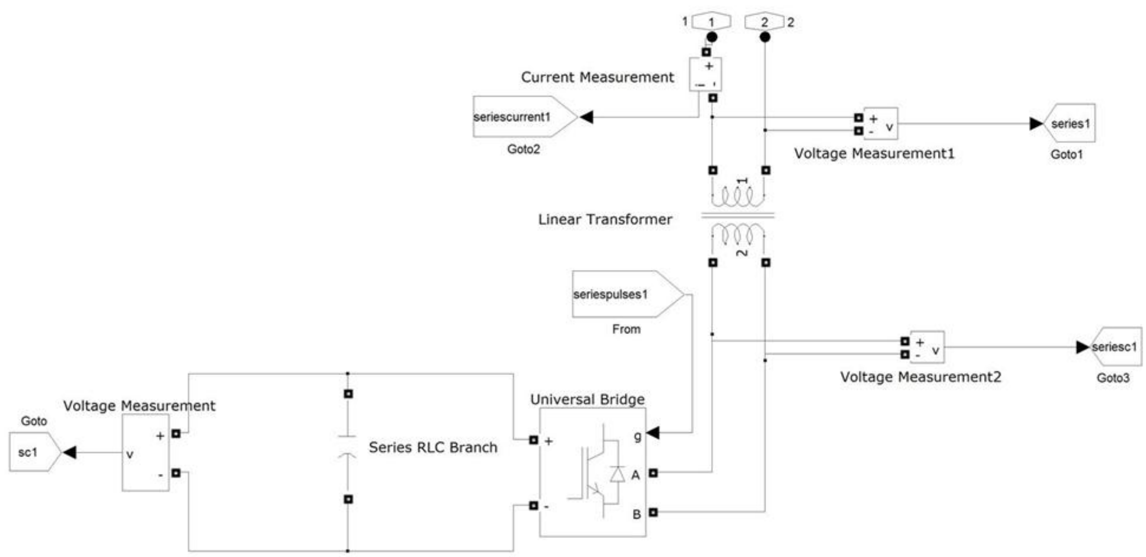


Figure 5-2 Subsystem of DPFC Simulink model

5.1.2 Series controller

This shows the internal circuitry of Series Controller with filters, timers, unit delay, discrete single phase PLLs, discrete PWM generators and reference voltages & currents.

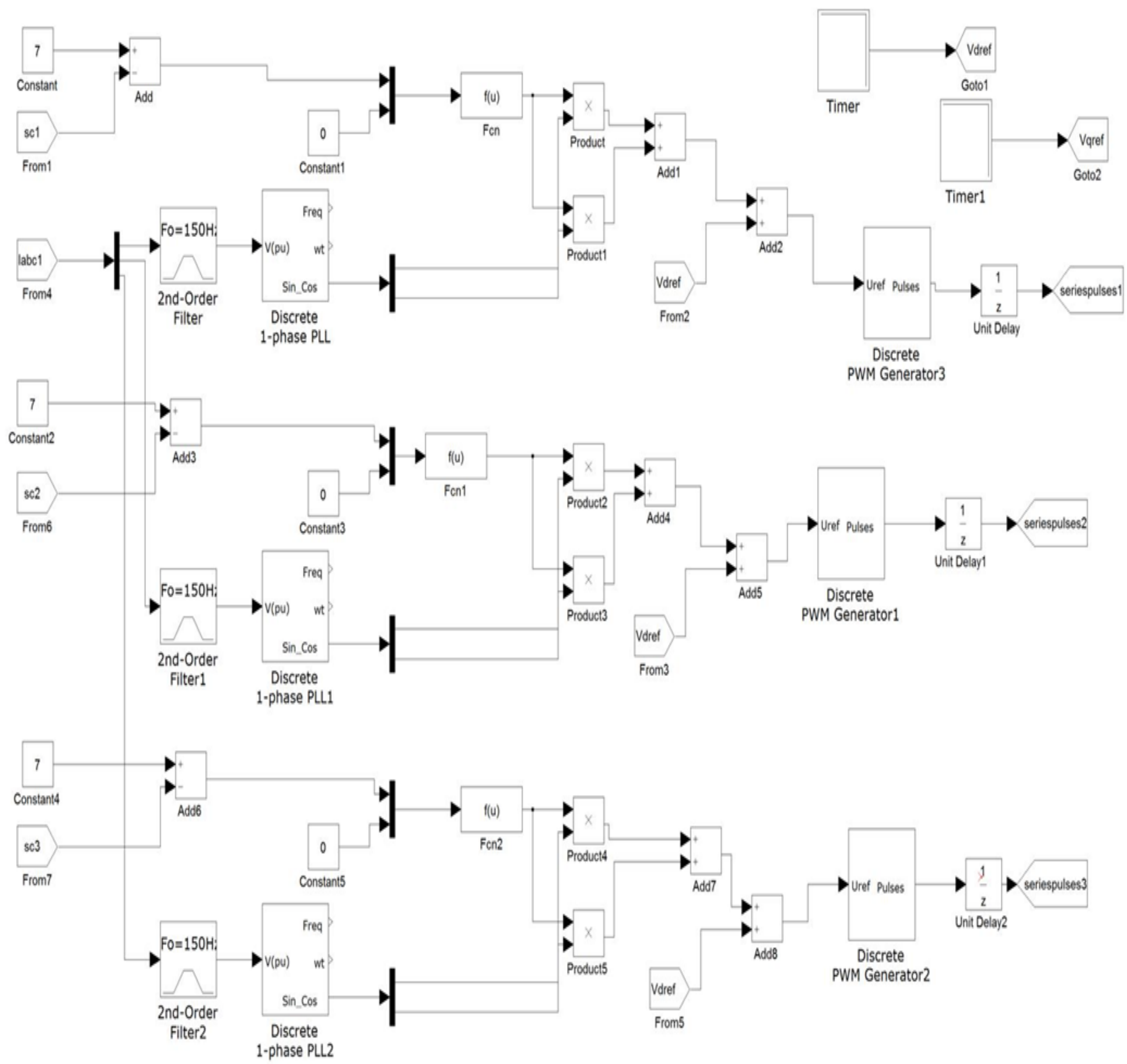


Figure 5-3 series controller

5.1.3 Shunt controller

This shows the internal circuitry of Shunt Controller with discrete PI controller, timers, unit delays, dq0-to-abc transformers, discrete three phase PLL, discrete PWM generators and reference voltages & currents.

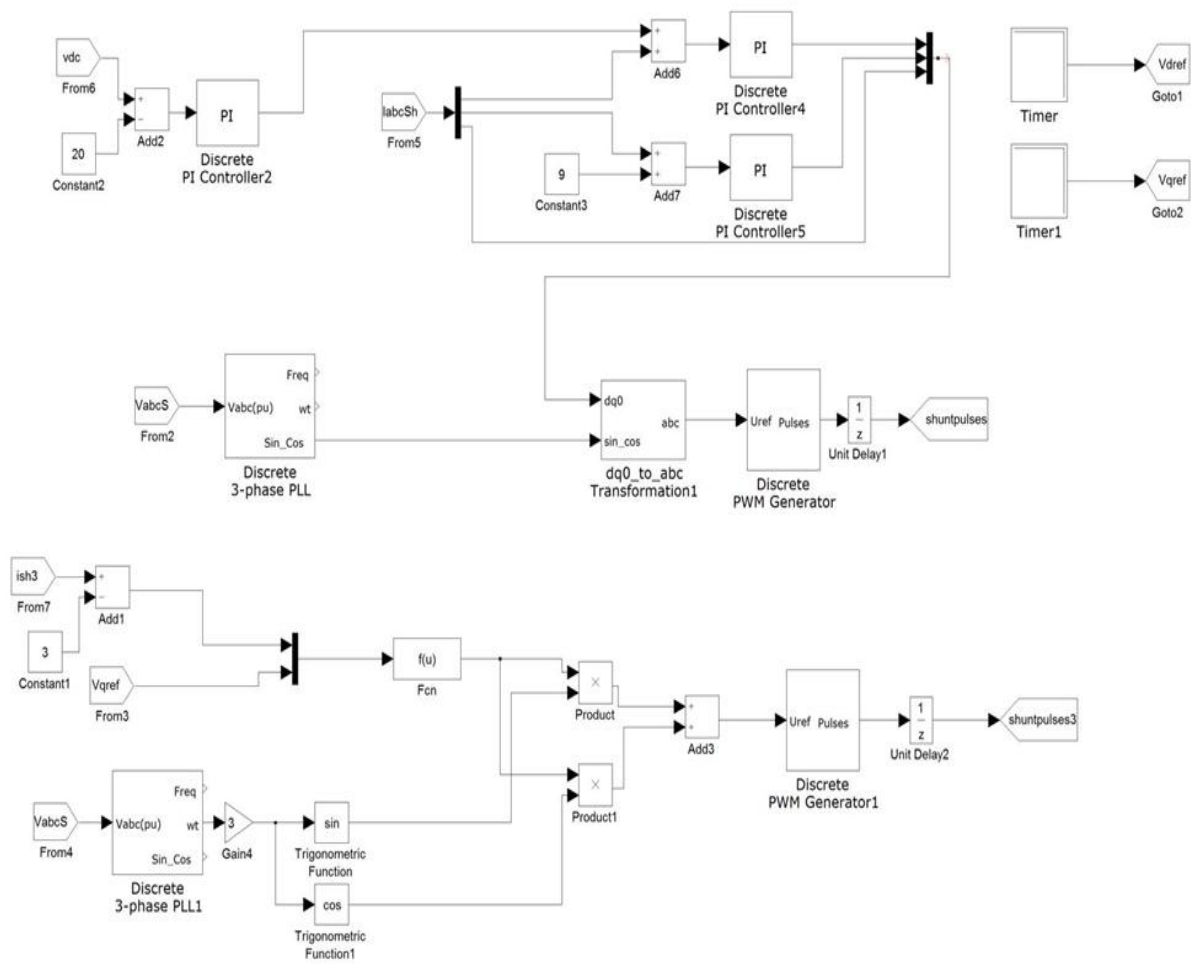


Figure 5-4 Shunt controller

5.1.4 Measurements

In this diagram we shows the different quantities which will be measure and plot into the form of wave form as the result of simulink.

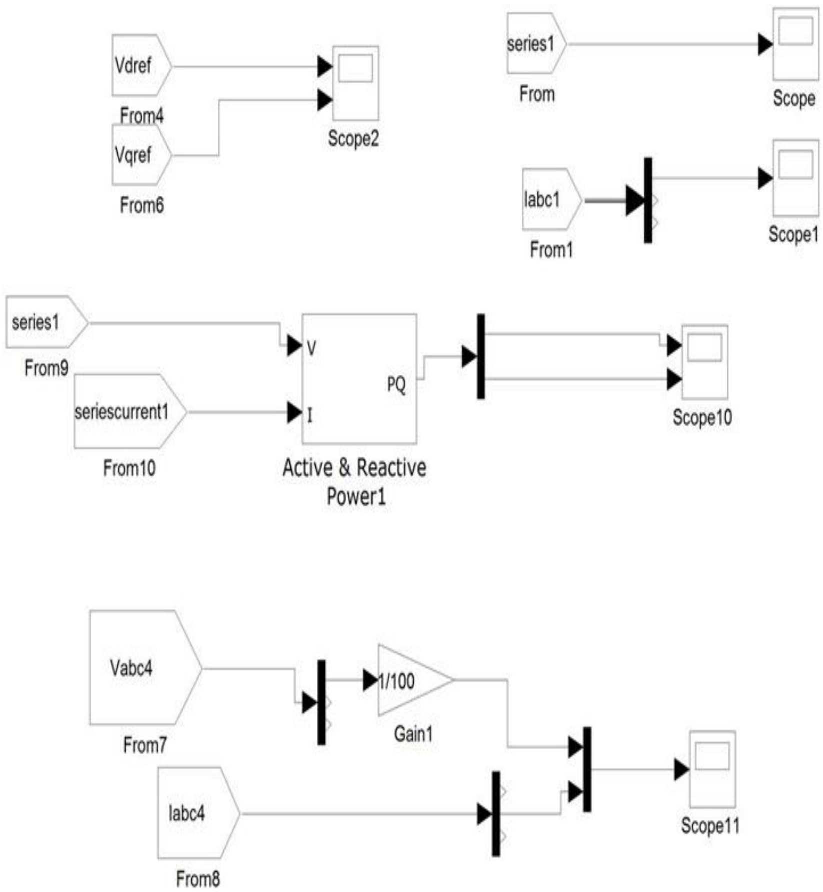


Figure 5-5 Measurements of Simulink

5.6 RESULTS

Step response of the DPFC: series converter voltage

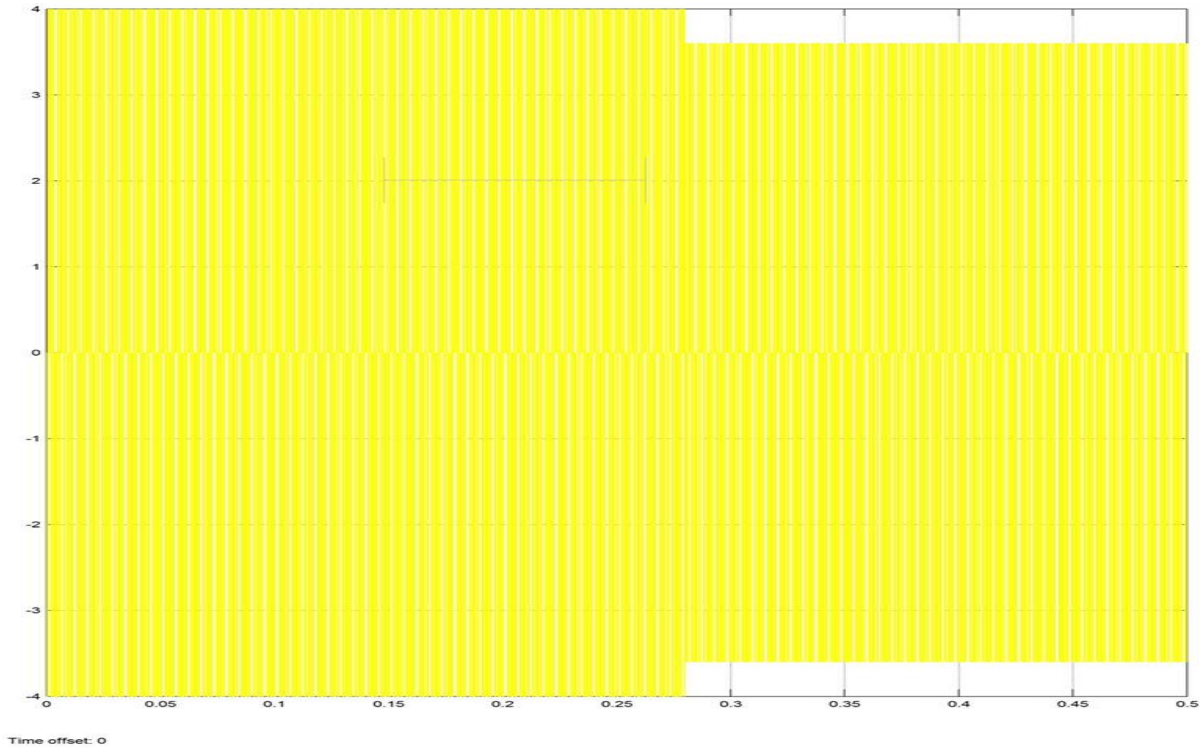


Figure 5-6 Step response of the DPFC: series converter voltage

***Line current, Step response of the DPFC*.**

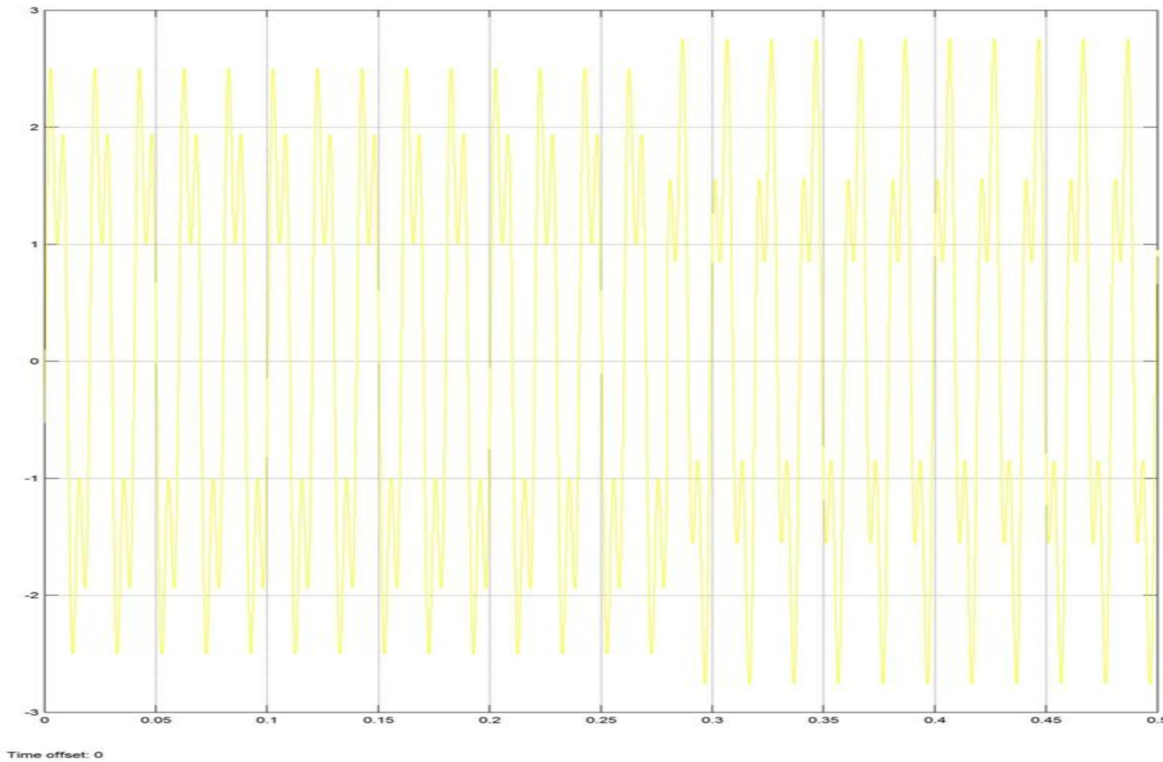


Figure 5-7 line current, Step response of the DPFC

Voltage & Current at Delta Side of T/F

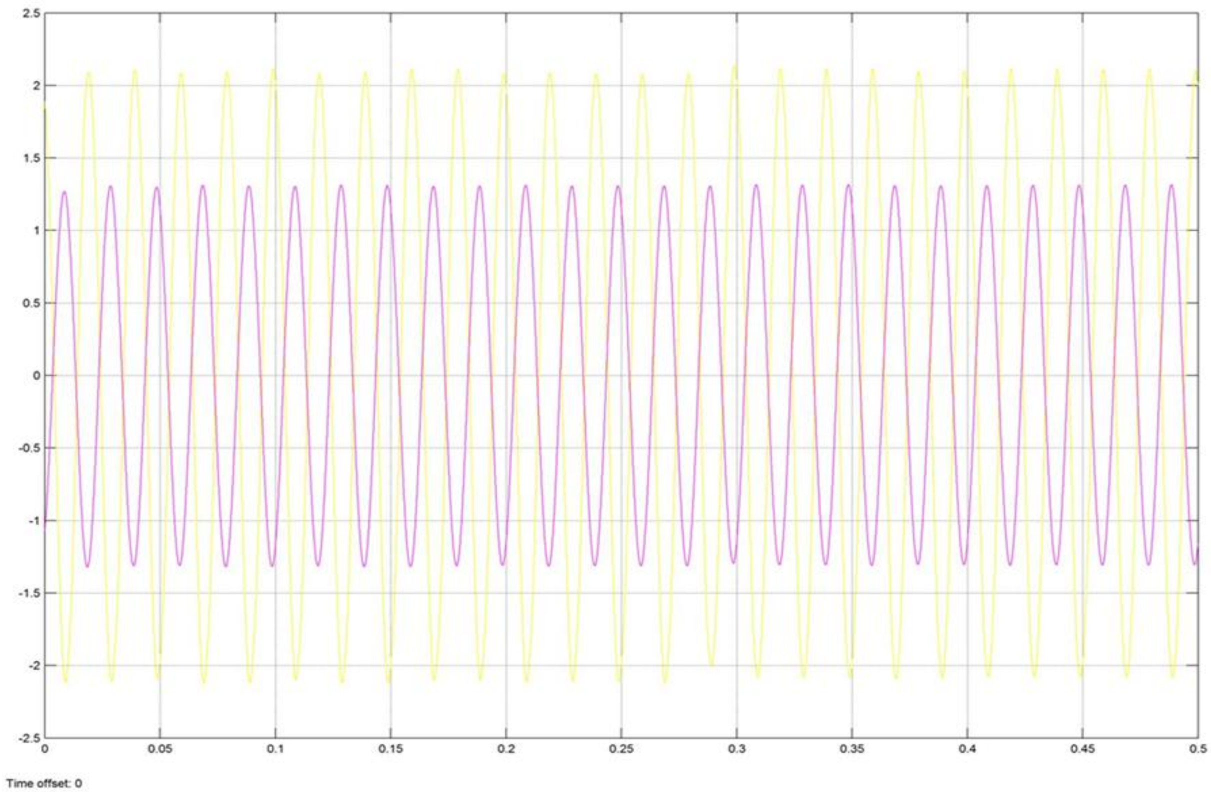


Figure 5-8 Voltage & Current at Delta Side Of T/F

Reference voltages for series converter at fundamental frequency

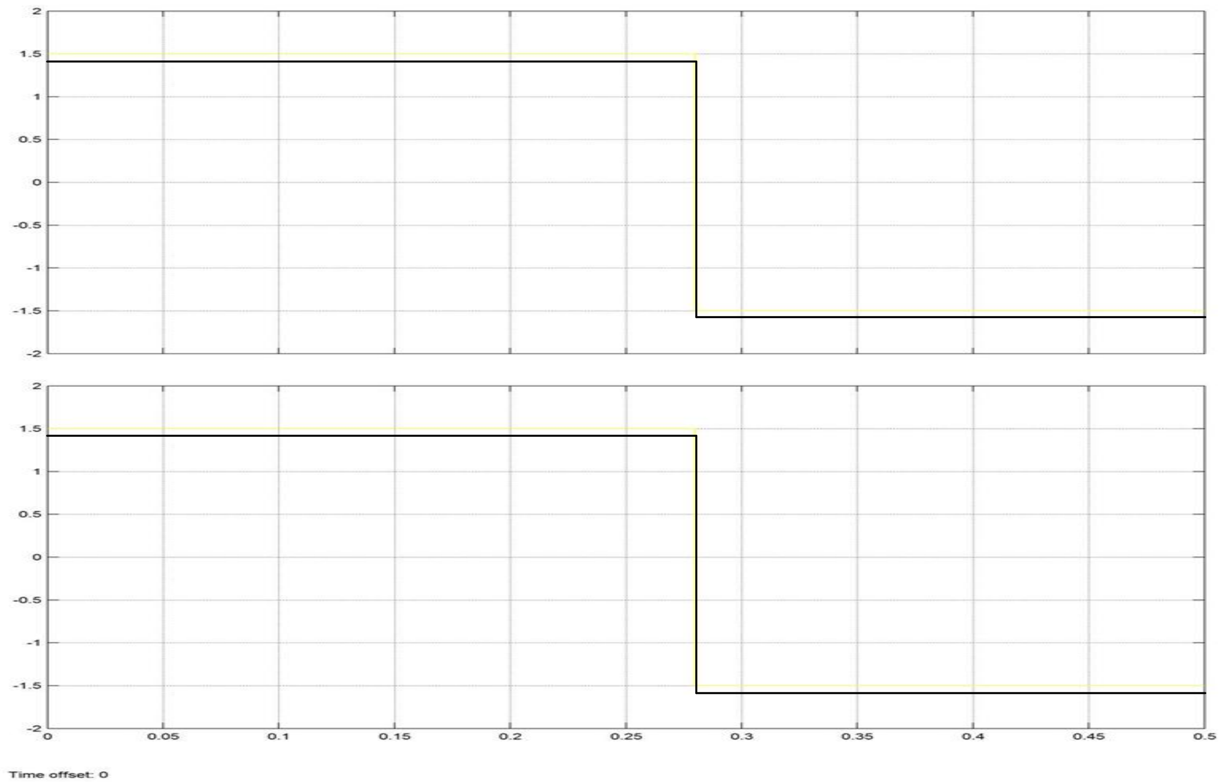


Figure 5-9 Reference voltages for series converter at fundamental frequency

Injection of active and reactive power by series converter at fundamental frequency

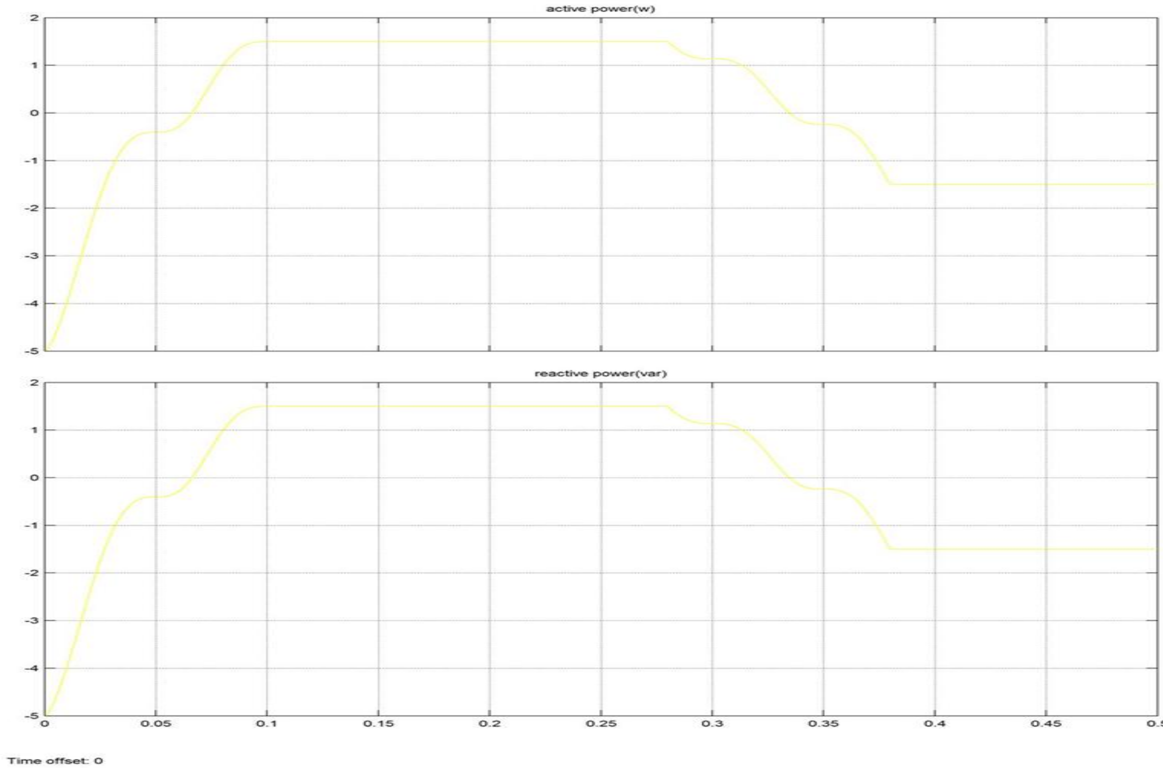


Figure 5-10 Injection of active and reactive power by series converter at fundamental frequency

5.7 RESULTS ANALYSIS

Figure 5-6 shows the simulink result of Step response of the DPFC as the output of series converter voltage with respect to time axes (voltage versus time). It has been observed that initially the voltage of the series converter is something higher than that of after 0.27 seconds. This is the required wave form because initially system wants more voltage for more reactive power consumption.

Figure 5-7 shows the simulink result of Step response of the DPFC as the output of current (line to line) with respect to time axes (Current versus time).

Figure 5-8 shows the simulink result of voltage & current at delta side of transformer. Actually this shows the voltage and current simultaneously in the same graph so that we can compare it time to time. In this simulink result voltage shows with the yellow color graph and current shows with violet color graph.

Figure 5-9 shows the simulink result of reference voltages for series converter at fundamental frequency. Critical point if reference voltages are 0.27 seconds. In this point reference voltage changes its value from positive value to negative value.

Figure 5-10 shows the simulink result of power (active & reactive) injected by series converter at fundamental frequency. This response clearly shows that, whenever the active power changes, simultaneously reactive power also changes accordingly. This is the main advantage of this project.

Chapter 6

6.1 CONCLUSION

As mentioned in Chapter 1, there is a high demand for power flow control in modern energy systems. The trend is that the mechanical power flow control devices (PFCDs) are gradually being replaced by Power Electronics (PE) PFCDs. Among all PE PFCDs, the Unified Power Flow Controller (UPFC) is the most versatile device. However, the UPFC is not widely applied in the power grid due to its high cost and relatively low reliability.

The aim of this thesis is the development of a new type of power flow control device. that offer the same control capability as the UPFC control, at reduced cost and greater reliability. The new device, distributed power flow controller (DPFC) is a further development of the UPFC. It also inherits the control capability of the UPFC, which is the simultaneous adjustment of the line impedance, transmission angle and the magnitude of the bus voltage. The common DC link between the series and shunt converters, used to exchange active power in the UPFC is removed. The series converter of DPFC uses the concept D-FACTS, which uses multiple small single-phase converters instead of a large inverter. DPFC reliability is greatly increased due to the redundancy of the series converters. The total cost of DPFC is also much lower than the UPFC, because no high voltage isolation is required and the rating of the components is quite low. It is proved that the shunt and series converters can exchange the DPFC active power at the third harmonic frequency and the series converters are able to inject controllable active and reactive power at the fundamental frequency.

6.2 FUTURE SCOPE

Day by day energy demand of INDIA increasingly greatly because of that reason we need to think some efficient manner to transmit the bulk power/energy from generating point to power station with the lesser cost of installation and great reliability.

The following study based on the present work can be extended in future we have seen that our system reliability improves with lesser cost of the controlling devices due to less insulation. The country like INDIA in which installation cost plays a great role to install new devices. So in future by using DPFC we save installation cost with improved performance of the system.

RFERENCES

[1] Y.H. Song and A. Johns, *Flexible ac Transmission Systems (FACTS)* (IEE Power and Energy Series), vol. 30. London, U.K.: Institution of Electrical Engineers, 1999.

[2] N. G. Hingorani and L. Gyugyi, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*. New York: IEEE Press, 2000.

[3] L.Gyugyi, C.D. Schauder, S. L.Williams, T. R. Rietman,D. R. Torgerson, and A. Edris, "The unified power flow controller: Anewapproach to power transmission control," *IEEE Trans. Power Del.*, vol. 10, no. 2, pp. 1085–1097, Apr. 1995.

[4] A.-A. Edris, "Proposed terms and definitions for flexible ac transmission system (facts)," *IEEE Trans. Power Del.*, vol. 12, no. 4, pp. 1848–1853, Oct. 1997.

[5] K. K. Sen, "Sssc-static synchronous series compensator: Theory, modeling, and application," *IEEE Trans. Power Del.*, vol. 13, no. 1, pp. 241–246, Jan. 1998.

[6] M. D. Deepak, E. B. William, S. S. Robert, K. Bill, W. G. Randal, T. B. Dale, R. I. Michael, and S. G. Ian, "A distributed static series compensator system for realizing active power flow control on existing power lines," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 642–649, Jan. 2007.

[7] D. Divan and H. Johal, "Distributed facts—A new concept for realizing grid power flow control," in *Proc. IEEE 36th Power Electron. Spec. Conf. (PESC)*, 2005, pp. 8–14.

[8] Y. Zhihui, S.W. H. de Haan, and B. Ferreira, "Utilizing distributed power flow controller (dpfc) for power oscillation damping," in *Proc. IEEE Power Energy Soc. Gen. Meet. (PES)*, 2009, pp. 1–5.

[9] Y. Zhihui, S. W. H. de Haan, and B. Ferreira, "Dpfc control during shunt converter failure," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, 2009, pp. 2727–2732.

[10] Y. Sozer and D. A. Torrey, "Modeling and control of utility interactive inverters," *IEEE Trans. Power Electron.*, vol. 24, no. 11, pp. 2475–2483, Nov. 2009.

[11] L. Huber, B. T. Irving, and M. M. Jovanovic, "Review and stability analysis of pll-based interleaving control of dcm/ccm boundary boost pfc converters," *IEEE Trans. Power Electron.*, vol. 24, no. 8, pp. 1992–1999, Aug. 2009.

[12] M. Mohaddes, A. M. Gole, and S. Elez, "Steady state frequency response of statcom," *IEEE Trans. Power Del.*, vol. 16, no. 1, pp. 18–23, Jan. 2001.

[13]N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*, 3rd ed. Hoboken, NJ: Wiley, 2003.

[14]X.-P. Zhang, E. Handschin , M. Yao,"Multi-control functional static synchronous compensator (STATCOM) in power system steady state operation", General ELSEVIER., July 2004.

[15] Xiao-Ping Zhang, "Advanced Modeling of the Multicontrol Functional Static Synchronous Series Compensator (SSSC) in Newton Power Flow", IEEE Trans. Power Systems., vol. 18., no.4, pp. , Nov. 2003.

[16]Yankui Zhang, Yan Zhang, and Chen Chen," A Novel Power Injection Model of IPFC for Power Flow Analysis Inclusive of Practical Constraints", IEEE Trans. Power Systems., vol. 21., no.4, pp.1550-1556 , Nov. 2006.

[17] Z. Yuan, S. W. H. de Haan, and B. Ferreira, "A New FACTS component: Distributed Power Flow Controller (DPFC)," in Power Electronics and Applications, 2007 European Conference on, 2007, pp. 1-4.

[18] N. H. Woodley, L. Morgan, and A. Sundaram, "Experience with an inverter-based dynamic voltage restorer," *IEEE Trans. Power Del.*, vol. 14, no. 3, pp. 1181–1186, Jul. 1999.

[19] Zhihui Yuan, Sjoerd W. H. de Haan, Jan Braham Ferreira and Dalibor Cvoric, “A FACTS Device: Distributed Power-Flow Controller (DPFC)”, *IEEE Transactions on Power Electronics,* vol. 25, no. 10, october 2010.

[20] Sarimalla Pedakotaiah and Santosh A, “Simulation of Distributed Power-Flow Controller (Dpfc)”, *International Journal of Engineering and Science* ISBN: 2319-6483, ISSN: 2278-4721, vol. 2, Issue 1 (January 2013), PP 25-32.

[21] O.Sushma and Dr. K. S. R. Anjaneyulu “Modelling Of Distributed Power Flow Controller (DPFC) Using Matlab/Simulation*”, International Journal of Engineering Research & Technology,* vol. 2 Issue 1, January- 2013 ISSN: 2278-0181.

[22] Zhihui Yuan, Sjoerd W.H. de Haan and Jan A. Ferreira, “Construction and first result of a scaled transmission system with the Distributed Power Flow Controller (DPFC)”, *Delft University of Technology* Mekelweg 4, 2628 CD.

[23] L. Gyugyi, "Unified power-flow control concept for flexible AC transmission systems," *Generation, Transmission and Distribution [see also IEE Proceedings-Generation, Transmission and Distribution], IEE Proceedings C,* vol. 139, pp. 323-331, 1992.

[24] Ahmad Jamshidi, S. Masoud Barakati, and Mohammad Moradi Ghahderijani, “Power Quality Improvement and Mitigation Case Study Using Distributed Power Flow Controller” *ECE Department, University of Sistan and Baluchestan, Iran.*

[25] P. Ramesh, Dr. M.damodara reddy, “ Modeling and Analysis of Distributed Power- Flow Controller (DPFC)” *International Journal of Engineering Research and Applications* ISSN: 2248-9622 ,vol. 2, issue 2,Mar-Apr 2012, pp.609-615.

[26]Z. Yuan, S.W.H. de Haan and J.A. Ferreira, “Control Scheme to Improve DPFC Performance during Series Converter Failures”

[27] P. Ramesh, Dr. M.damodara reddy, “Control design and simulation of distributed Power-flow controller (DPFC)”, *ARPN Journal of Engineering and Applied Sciences* ISSN 1819-6608, vol. 7, no. 6, june 2012.