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DISTRIBUTED POWER FLOW CONTROLLER USING MATLAB/SIMULINK

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DECLARATION

We hereby declare that we carried out the work reported in this report in the Department of Electrical & Computer Engineering, University of wolkite under the advisors of Mr.Gemedo. We solemnly declare that this thesis has been written based on the works and results found by us, by the help of our advisers & different sources. All sources of knowledge used have been duly acknowledged.

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ABSTRACT

This work presents a new component within the flexible ac-transmission system (FACTS) family, called distributed power flow controller (DPFC). The proposed DPFC will be derived from the unified power-flow controller (UPFC). The DPFC can be considered as a UPFC with an eliminated common dc link. The active power exchange between the shunt and series converters, which is through the common dc link in the UPFC, is now through the transmission lines at the third-harmonic frequency. The DPFC employs the distributed FACTS (D-FACTS) concept, which is to use multiple small-size single phase converters instead of the one large-size three-phase series converter in the UPFC. The large number of series converters provides redundancy, thereby increasing the system reliability. As the D-FACTS converters are single phase and floating with respect to the ground, there is no high-voltage isolation required between the phases. Accordingly, the cost of the DPFC system is lower than the UPFC. The DPFC has the same control capability as the UPFC, which comprises the adjustment of the line impedance, the transmission angle, and the bus voltage. The principle and analysis of the DPFC will be presented in this work and the corresponding simulation results will be shown.

Key words: AC/DC converters, power flow controller, third harmonic frequency, DPFC, power electronics, transmission line parameters control.

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ACRONYMS

DPFC =Distributed power flow controller

UPFC =Unified power flow controller

DC =Direct-current

AC = Alternative –current

IEEE=International electrical and electronic engineering

STATCOM = Static synchronous compensator

SSSC= Static synchronous series compensator

FACTS = Flexible alternative current transmission system

D-FACTS =Distributed flexible alternative current transmission system

THD= Total harmonic distortion

PF =Power factor

DFT =Distortion fundamental trigonometric

IEC=Integrated electronic circuit

SVC= Static variable compensator

EMI= Magnetic force interface

RFI = Resistance frequency interface

DFC = Dynamic flow controller

VSC =Voltage source converter

TCSC =Thyristors controlled series compensator

HVDC =High voltage direct controller

HVDC B2B =High voltage direct controller back to back

VSC B2B = Voltage source converter back to back

TSR =Thyristors switched reactor

TCR =Thyristors controlled reactor

TSC =Thyristors switched capacitor

FC = Fixed capacitor

IPFC = Interline power flow controller

DIPFC =Distributed interline power flow controller

IGBTs = Insulated gate bipolar transistors

IGCTs = Insulated gate communicated Thyristors

GTO = Gate Thyristors on

PWM = Pulse width modulated

PST = Phase shifting transformer

MSC = Mechanical switched capacitor

VSI = Voltage supply inverter DSSC =Distributed

PLL =Phase-Lock-Loop

CHAPTER ONE

1.1 Introduction

The increasing demand and the nature of networks build is necessary to regulate the facility flow in power transmission systems quick and faithfully. The versatile ac transmission (FACTS) that is distinct by IEEE as “a power electronic primarily based system and any static instrumentation that provides management of one or alternative ac transmission parameters to boost the management ability and also the increase of power transfer capability” which are often used for power flow control. Now, the Unified Power Flow Controller (UPFC) is that the most powerful FACTS device, which might instantly management all the parameters of the system the road electrical resistance, transmission angle and bus voltage [1].

The UPFC is that the combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC), that area unit along via a standard dc link, to permit the bi directional flow of active power between the series output terminals of a SSSC and also the shunt output terminals of a STATCOM [7]. The device is asynchronous with the road offers the most operate of associate degree UPFC by injecting the four quadrant voltage with manageable magnitude and section. The injected voltage acts as a synchronous ac voltage supply that is employed to vary the transmission angle and line electrical resistance, therefore severally dominant the active and also the reactive power flow through the road. The series voltage leads to active and reactive power injection or immersion between series device and cable [4].This reactive power is made internally by the series device and also the active power is provided by the shunt device that's consecutive connected. The shunt device controls the voltage of a dc condenser by fascinating or generating active power from the bus. Consequently, it acts as a synchronous supply in parallel with the system just like the STATCOM; the shunt device may also be offered reactive compensation for the bus [9].

The elements of the UPFC handle the voltages and currents with high rating. Therefore, the overall price of the system is high. Attributable to the common dc link interconnection, a failure that happens at one amongst the device can have an effect on the total system. To attain the specified reliable ness for power systems, bypass circuits and redundant backups (backup electrical device, etc.) area unit needed, that on alternative hand, to extend the value. Consequently, the UPFC isn't commercially used however it's the foremost advanced management capabilities. This project presents a replacement plan, known as the distributed power flow controller (DPFC) that is derived from the UPFC. Constant because the UPFC, the DPFC is ready to regulate all of the system parameters [16].

The DPFC removes the common dc link among the shunt and the series converters. The active power exchange between the shunt and series device through the cable at the third harmonic frequency. The series device of the DPFC works the distributed FACTS (DFACTS) conception. Comparison with the UPFC, the DPFC have two major advantages, 1) low price owing to the low voltage isolation and also the low part rating of the series device and 2) high reliable ness owing to the redundancy of the series converters. This initiates with proposing the principle of the DPFC, followed by its steady-state analysis[13]. Next a brief introduction of the DPFC management and also the paper ends with the experimental results of the DPFC.

1.3 OBJECTIVE

1.3.1 General objective

The main objective of this thesis work is to study, analysis and design for power flow equipment by using DPFC to improve power quality.

1.3.2 Specific objective

The specific objectives of this project is power quality improvement .power quality is the index in which both the delivery and consumption of electric power effect on the performance of electrical apparatus. These are:

- Increase of transmission capability.
- Voltage control.
- Reactive power compensation.
- Stability improvement.

1.4 Statement of problem and formulation

The fast changes in the electrical load profile from nonlinear sort have been generated continuing power quality issues that area unit tough to discover. The foremost important contributor to the facility quality issues is that the customers (or end-user electrical loads) that uses of sensitive sort nonlinear load altogether sectors (Industrial, Commercial and Residential). Power Quality issues can be roughly broken into a number of sub-categories such as harmonics (integral,sub,super and inter-harmonic),voltage swells, sags, flicker and transients.in addition to this lower order harmonics causes the intense concern within the electrical distribution or utilization system.

1.5 Scope of the project

Our thesis involves modeling, analysis and of each component and software simulation of the system. Due to material availability shortage this thesis is limited up to software simulation only. The performance analysis in this thesis work is accomplished be based on analytical analysis and computer simulation of the system using MATLAB software. This thesis deals with improvement power flow depend up on power distributed through transmission line. The electrical power that could be distributed is limited to electrical appliance (devices) with less power consumption, as like:

- DC LINK.
- Exchange active and reactive to balance power flow.
- Reduction of distortion.

1.6 outline of the thesis

This thesis contains the following parts

Chapter 1: This Chapter gives an introduction to the concept of power quality improvement using distributed power flow controller, background of the thesis, statement of the problem, proposed solution, and scope of the project, objective and outline of the report.

Chapter 2: This chapter contains Literature review.

Chapter 3: This chapter discusses various. System block diagram and its brief descriptions, overview of distributed power flow controller (DPFC) and DPFC modeling.

Chapter 4: This chapter explains: System design and implementation

Chapter 5: This chapter contains conclusion, recommendation and reference.

CHAPTER TWO

2. Literature Review

A. Hannam and Azah [2005][2], Active filtering of an electrical power has become a developed technology for harmonic and reactive power compensation in two-wire (single phase), three-wire (three section while not neutral), and four-wire (three section with neutral) ac power networks with nonlinear masses. A comprehensive estimation of active filter (AF) configurations, management ways, choice of elements, alternative connected economic and technical issues, and their choice for specific applications. It's aimed toward providing a broad perspective on the standing of AF technology to researchers and application engineers managing the facility quality problems [2].

B. Singh, K.Al-Haddad, [2015][1] The proper issue of modeling and analysis of custom power controllers, a replacement generation of power physics primarily based instrumentation aimed toward enhancing then liableness and quality of power flows in low voltage distribution networks. The well-developed graphic facilities offered in associate degree business normal facility package, specifically PSCAD/EMTDC, area unit wont to conduct all options of model implementation and to hold out in depth simulation studies. Graphics primarily based models appropriate for magnetic force transient studies area unit existing for the subsequent three custom power controllers: the distribution static compensator (D-STATCOM), the dynamic voltage reserves (DVR), and also the solid state transfer switch (SSTS) [1]. C. Zhihui Yuan, Sjoerd W.H de Haan,[2010][4] The DPFC springs from the unified power flow controller (UPFC). The DPFC are often thought-about as a UPFC with are moved common dc link. The active power exchange between the shunt and series converters, through the common dc link within the UPFC, is currently through the transmission lines at the third harmonic frequency. The DPFC works as a distributed FACTS conception that is to be used multiple little size single section devices replaced with the one giant size three section series converter within the UPFC. The large variety of series converters area unit offer redundancy, therefore increasing the system liableness. Therefore, the value of the DPFC system is under the UPFC.

2.1 Power quality

Power quality has become one amongst the foremost productive ideas within the power business since 1980's. Varied sources area unit used this term "Power quality" with completely different meanings. Alternative sources use similar however slightly completely different nomenclature like "quality of power supply" or "voltage quality". The aim of facility has continuously been to produce current to the purchasers. Power Quality conception in the main deals with three factors specifically reliable ness, Quality of provide and client service. "Power quality may be a set of electrical boundaries that permits a bit of apparatus to operate in its meant manner while not important loss of performance or lifetime." This definition embraces things that we tend to demand from associate degree device performance and lifetime. Any power-related downside that compromises either attribute may be a power quality concern.

Power quality could also be outlined because the "degree to that each the employment and delivery of electrical power affects the performance of electrical instrumentation.

"From a client perspective, an influence quality downside is outlined as "Any power downside manifested in voltage, current or frequency deviations that leads to equipment failure or disoperation of client instrumentation. In a three power system, unbalanced voltages also are an influence quality downside. Two power quality issues are known as major concern to the purchaser's area unit voltage sags and harmonics. .

2.2 Power quality disturbances

In electrical power system, there are a unit varied styles of power quality disturbances. There is a unit the Thyristors classified into different classes and their explanations are necessary so as to classify the measurement results and to defined magnetic force development, which might cause power quality issues. Some disturbances area unit come back from the availability network, whereas others area unit made by the load itself. The classes are often classified as follows short-duration voltage variations, long duration voltage variations, transients, voltage imbalance, waveforms distortion, voltage fluctuation and Power frequency variations.

2.3 short-duration voltage variations

There are unit three varieties of short length voltage variations, specifically instant, short and temporary, counting on its length. Short length voltage variations are a unit caused by the fault conditions and also the energization of enormous masses, which needs high beginning currents and loose connections in power wiring. Counting on the fault location and also the system conditions, the fault will generates sags, swells or interruptions. The fault condition is often near the purpose of interest or isolated from the purpose of interest. Throughout the particular fault condition, the impact of the voltage is of the short variation till protecting devices area unit operate to clear the fault.

2.4 Voltage Sag and Swell Definitions

Over the last fifteen years, supported the facility quality measurement instruments voltage sags and swell definitions are developed. Facility communities state sags or dips as a discount in voltage below the rated worth between one cycle and a pair of 55 seconds. Surges area unit currently known as swells, except that the voltage exceeds a selected user-defined high limit. whereas completely different definitions relating the amplitude and length area unit still in use, the IEEE 1159-1995 counseled observe on observance power Quality has outlined them as follows.

Sag (dip) are often outlined as, “According to the IEC, a provide voltage dip may be a sharp reduction in provide voltage to a worth between ninetieth and a hundred and twenty fifth of the declared voltage. In keeping with IEEE a drop is just a sag if the length of sag voltage is between 100 percent and ninetieth of traditional voltage.”Swell are often outlined as, “An increase between 0.1 Pu to 1.8 Pu in rms voltage or current at the facility frequency durations from 0.5 to 1 minute. With reference to associate degree outage or interruption, sag is differentiated by the amplitude being larger than or up to 0.1 Pu (of nominal voltage).

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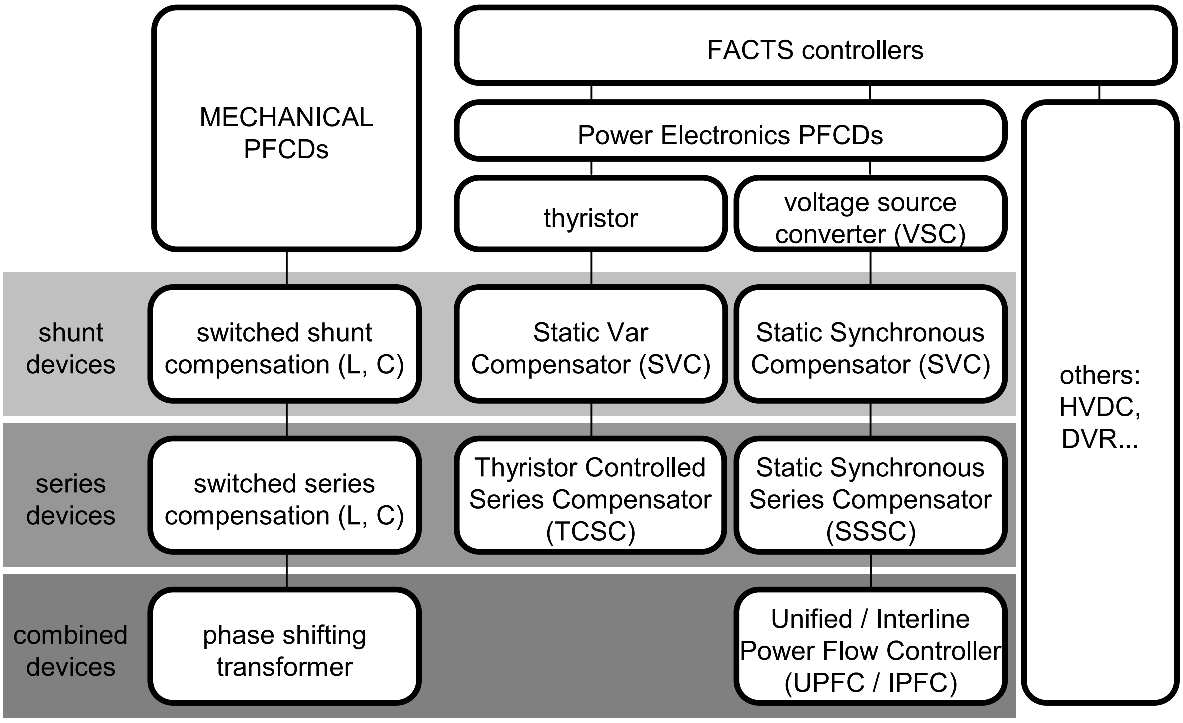

The left column in table one contains the standard devices build out of mounted or automatically switchable elements like resistance, inductance or capacitance organized with transformers. The FACTS devices contain these components similarly however use extra power electronic valves or converters to modify weather in smaller steps or with change patterns at intervals a cycle of the electricity. The left column of FACTS devices uses Thyristors valves or converters. These valves or converters area unit accepted since many years. They need low losses owing to their low change frequency of once a cycle within the converters or the usage of the Thyristors to easily bridge impedances within the valves. The right column of FACTS devices includes additional advanced technology of voltage supply converters primarily based nowadays in the main on Insulated Gate Bipolar Transistors (IGBT) or Insulated Gate Commutated Thyristors (IGCT). Voltage supply Converters offers a free manageable voltage in magnitude and section attributable to a pulse dimension modulation of the IGBTs or IGCTs. High modulation frequencies enable to induce low harmonics within the sign and even to compensate disturbances coming back from the network. The disadvantage is that with associate degree increasing change frequency, the losses area unit increasing similarly. Hence, special styles of the converters area unit necessary to compensate this.

2.5 Configurations of facts devices

2.5.1 Shunt Devices

The largely used FACTS device is that the SVC or the version with Voltage supply device known as STATCOM. These shunt devices area unit operational as reactive power compensators. The most applications in transmission, distribution and industrial networks are

Reduction of unwanted reactive power flows and therefore reduced network losses

Improvement of static or transient stability.

Almost half the SVC associate degreed quite half the STATCOMs area unit used for an industrial applications.

2.5.2 Static var compensator (SVC)

Electrical masses area unit each generate and absorb reactive power. Since the transferred load varies significantly from one hour to a different, the reactive power balance in a very grid varies as fine. The results are often undesirable voltage amplitude variations or maybe a voltage depression, at the intense voltage collapse.

Applications of the Svc systems in Transmission systems

- To increase active power transfer capacity and transient stability margin
- To damp power oscillations
- To achieve effective voltage control

2.5.3 Statcom

The STATCOM includes a characteristic associated to the synchronous condenser, however as associate degree device it's no inertia and is superior to the synchronous condenser in many ways in which, like higher dynamics, a lower investment price and lower operational and maintenance prices. A STATCOM is constructed with Thyristors with shut down capability like GTO or nowadays IGCT or with additional and additional IGBTs.

The advantage of a STATCOM is that the reactive power facility is freelance from the particular voltage on the association purpose.

2.5.4 Series devices

Series devices have been further developed from fixed or mechanically switched compensations to the Thyristors Controlled Series Compensation (TCSC) or even Voltage Source Converter based devices.

Main Applications Are

- Reduction of series voltage decline in magnitude and angle over a power line,
- Reduction of voltage fluctuations within defined limits during changing power transmissions,

2.5.5 TCSC

Thyristors Controlled Series Capacitors (TCSC) addresses specific driving issues in transmission systems. Primarily it will increase damping once giant electrical systems area unit interconnected. Second it will overcome the matter of Sub Synchronous Resonance (SSR), a development that involves associate degree interaction between giant thermal generating units and also the series stipendiary transmission systems.

From a principle technology purpose of read, the TCSC resembles the standard series condenser.

Advantages

- Continuous control of desired compensation level
- Direct smooth control of power flow within the network
- Improved capacitor bank protection
- Damping of electromechanical (0.5-2 Hz) power oscillations which often arise between areas in a large interconnected power network. These oscillations are due to the dynamics of inter area power transfer and often exhibit poor damping when the aggregate power transfer over a corridor is high relative to the transmission strength.

2.6 Remove DC Link and Active Power Exchange

In DPFC structure, transmission line makes the common connection between series and shunt converters. That is the reason for active power exchange between two converters. According to Fourier technique, non-sinusoidal voltage and current is equal to the summation of sinusoidal component in different frequencies with different amplitudes. The complete method is based on power theory of non-sinusoidal components [2]. The definition of active power getting from non sinusoidal voltage and current is mean value of the product of voltage and current. Since the integrals of all the cross product of terms with different frequencies are zero, the active power can be expressed by,

$$P= \sum_{i=1}^{\infty} V_i \, I_i \, Cos\emptyset_i \qquad (1)$$

Where Vi and Ii are the voltage and current at the ith harmonic frequency respectively, and i is the corresponding angle between the voltage and current. Equation (1) presents the active powers at different frequencies are independent from each other and the voltage or current at one frequency has no affect on the active power at other frequencies. The independence of the active power at different frequencies gives the possibility that a converter without a power source can generate active power at one frequency and absorb this power from other frequencies.

$$Pr + jQr = Vr. \, I^* \qquad (2)$$

According to above procedure in the DPFC, the shunt (STATCOM) converter can take active power from the line at fundamental frequency and return it back at a harmonic frequency. This active power flows through transmission line. So whatever amount of active power required at fundamental frequency is supplied by DPFC series converter which produces voltage at harmonic frequency. In this way active power is absorbed from harmonic components. Neglecting losses, the active power generated at the fundamental frequency is equal to the power absorbed at the harmonic frequency.

2.7 Using Third Harmonic Components

The 3rd harmonic is selected for active power exchange in the DPFC because of its unique features. . In a three-phase system, the 3rd harmonic in each phase is similar, which means they are ‘zero sequence’ components. Because the zero-sequence harmonic can be naturally blocked by YΔ transformers therefore there is no extra filter required to prevent harmonic leakage. 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. The relationship between the exchanged active power at the ith harmonic frequency Pi and the voltages generated by the converters is expressed by the well known the power flow equation and given as:

$$P_i = \frac{|V_{sh,i}||V_{se,i}|}{X_i} \text{Sin}(\emptyset_{sh,i} - \emptyset_{se,i}) \qquad (3)$$

Where Xi is the line impedance at ith frequency, |Vsh,i| and |Vse,i| are the voltage magnitudes of the ith harmonic of the shunt and series converters [3]. The impedance of transmission line has capacity to limits active power exchange through it.

CHAPTER THREE

3. System design and analysis

Flexible AC Transmission Systems, known as FACTS, no inheritable within the recent years a accepted term for higher controllability in power systems by means that of power electronic devices. Many FACTS devices are introduced for varied applications worldwide. Variety of recent varieties of devices area unit within the stage of being introduced in observe.

In most of the applications the controllability is employed to avoid price intensive or landscape requiring extensions of power systems, as an example like upgrades or additions of substations and power lines. FACTS devices offer an improved adaptation to variable operational conditions and improve the usage of existing installations. The fundamental applications of FACTS devices are Power flow control, Voltage control, Reactive power compensation, Power quality improvement and Interconnection of renewable and distributed generation and storages. Fig.3.1 shows the fundamental plan of FACTS for transmission systems. The usage of lines for active power transmission ought to be ideally up to the thermal limits. Voltage and stability limits shall be shifted with the means that of the many completely different FACTS devices. It are often seen that with increasing line length, the chance for FACTS devices gets additional and additional necessary.

The impact of FACTS devices is earned through switched or controlled shunt compensation, series compensation or section shift management. The devices work electrically as quick current, voltage or electrical resistance controllers. The facility electronic permits terribly short reaction times right down to so much below one second.

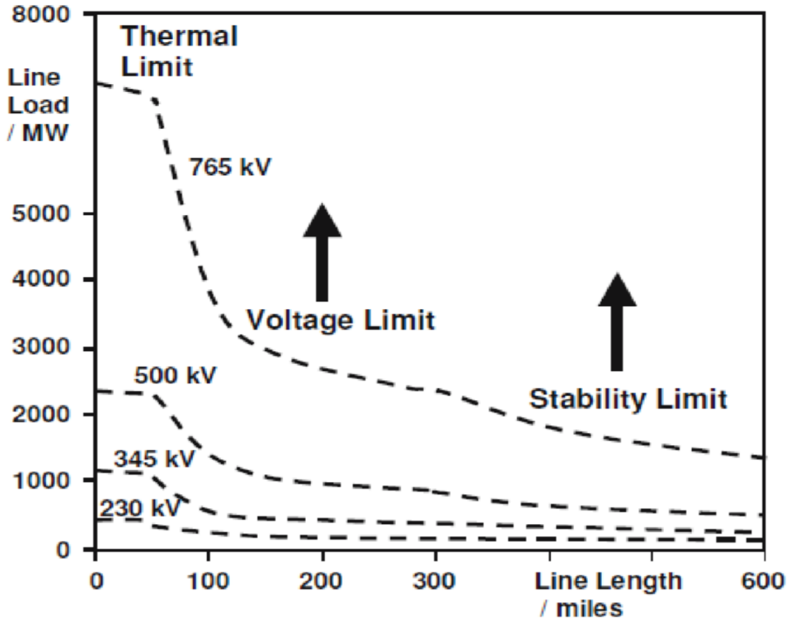

Figure 3.1 Operational Limits of Transmission lines For Different Voltage levels

The development of FACTS devices has started with the rising capabilities of power electronic elements. Devices for prime power levels are created offered in converters for prime and even highest voltage levels.

3.1. Unified power flow controller

The UPFC is a combination of a static compensator and static series compensation. It Acts as a shunt compensating and a phase shifting device simultaneously.

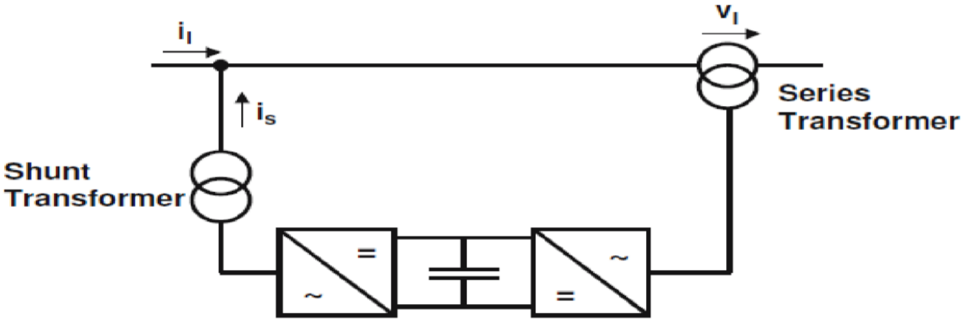

Figure 3. 2 Principle Configuration of DPFC

The UPFC includes of a shunt and a series electrical device, that area unit connected via two voltage supply converters with a standard DC condenser. The DC circuit permits the active power exchange between shunt and series electrical device to regulate the section

3.2 Operating Principle of UPFC

The simple elements of the UPFC area unit two voltage supply inverters (VSIs) sharing a standard dc storage condenser, and connected to the facility system through coupling transformers. One VSI is connected to in shunt to the transmission via a shunt electrical device, whereas the opposite is connected asynchronous through a series electrical device. A basic UPFC functional scheme is shown in Fig.3.3

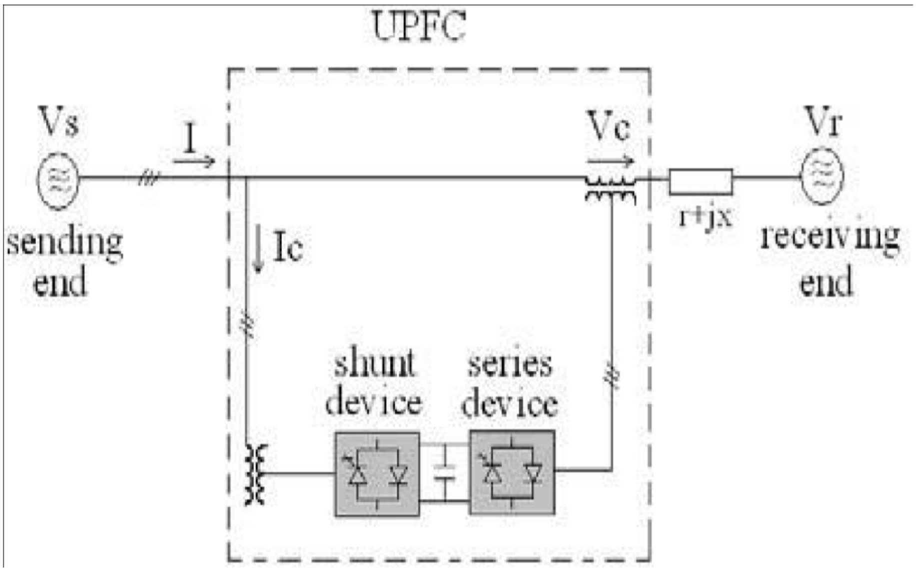

Figure 3.3 Basic UPFC functional Diagram

The series electrical converter is controlled to inject a symmetrical 3 section voltage system (Vse) of manageable magnitude and point in time asynchronous with the road to regulate active and reactive power flows on the cable. So, this electrical converter can exchange active and reactive power with the road. The reactive power is electronically provided by the series electrical converter, and also the active power is transmitted to the dc terminals. The shunt electrical converter is operated in such some way on demand this dc terminal power (positive or negative) from the road keeping the voltage across the storage condenser V_{dc} constant. So, internet real power absorbed from the road by the UPFC is equal solely to the losses of the inverters and their transformers. The remaining capability of the shunt electrical converter is often wont to exchange reactive power with the road therefore to supply a voltage regulation at the association purpose.

The two VSIs will work severally one another by separating the dc aspect. Therefore in this case, the shunt electrical converter is working as a STATCOM that generates or absorbs reactive power to control the voltage magnitude at the association purpose. Instead, the series electrical converter is working as SSSC that generates or absorbs reactive power to normalize the present flow, and therefore the facility flow on the cable.

The UPFC has several attainable operational modes. Specifically, the shunt electrical converter is working in such some way to inject a manageable current, is into the cable. The shunt electrical converter is often controlled in two completely different modes are:

Var Control Mode: The reference input is an inductive or capacitive VAR request. The shunt inverter control translates the var reference into a corresponding shunt current request and adjusts gating of the inverter to establish the desired current. For this mode of control a feedback signal representing the dc bus voltage, Vdc, is also required.

Automatic Voltage Control Mode: The shunt inverter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference value. For this mode of control, voltage feedback signals are obtained from the sending end bus feeding the shunt coupling transformer.

Direct Voltage Injection Mode: The reference inputs are directly the magnitude and phase angle of the series voltage.

3.3 Distributed power flow controller

In the previous chapter, a summary was given of mechanical and alphabetic character primarily based PFCDs as a result of high management capability, the alphabetic character primarily based combined PFCs, especially the UPFC and therefore the IPFC are appropriate for the long run power systems. Though, the UPFC and IPFC are not often times applied in repetition, to their high price and therefore the susceptibleness to failures. Generally, the dependability will be improved by reducing the quantity of parts. However, this can be uphill to the complicated topology of the UPFC and IPFC. To scale back the failure rate of the parts by choosing parts with higher ratings then essential or participating redundancy at the part or system levels also are choices. Sadly, these solutions will increase the initial investment necessary, negating any price connected benefits. Therefore, new approaches are required so as to extend dependability and cut back price of the UPFC and IPFC at an equivalent time.

After learning the failure mode of the combined FACTS devices, it's found that a standard DC link between converters cut back the dependability of a tool, as a result of a failure in one device can give the full device thus the DC link. By removing this DC link, the converters among the FACTS devices are operated severally, therefore increasing their dependability. The elimination of the common DC link additionally permits the DPFC construct will be applied to series converters. There in case, the dependability of the new device is additional improved to the redundancy provided by the distributed series converters. Additionally, series device distribution reduces price as a result of no high voltage isolation and high power rating parts are needed at the series half.

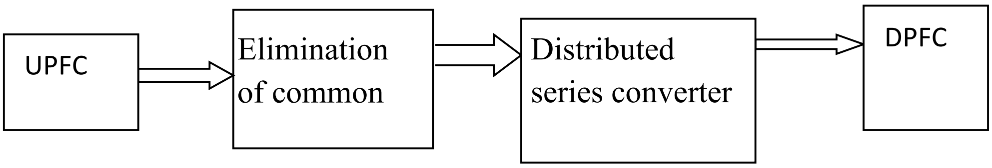

Figure 3.4 Block diagram of converting UPFC to DPFC

3.3.1 Topology operating principle of dpfc

In this section, DPFC topology and operating principle two methodologies are applied to the UPFC to extend the dependability and to scale back the value, they're as follows. First, eliminating the common dc link of the UPFC and second distributing the series device. By combining these 2 approaches, the new FACTS device DPFC is earned. The DPFC consists of one shunt and several other series-connected converters. The shunt device is analogous to a STATCOM, whereas the series device employs the D-FACTS construct that is to use multiple single part devices rather than one massive rated converter. Every device among the DPFC is freelance and has its own dc condenser to supply the desired dc voltage. The DPFC is able to control all system parameters. The DPFC eliminates the common dc link between the shunt and series converters. The active power exchange between the shunt and the series converter is through the transmission line at the third-harmonic frequency. The series converter of the DPFC employs the distributed FACTS.

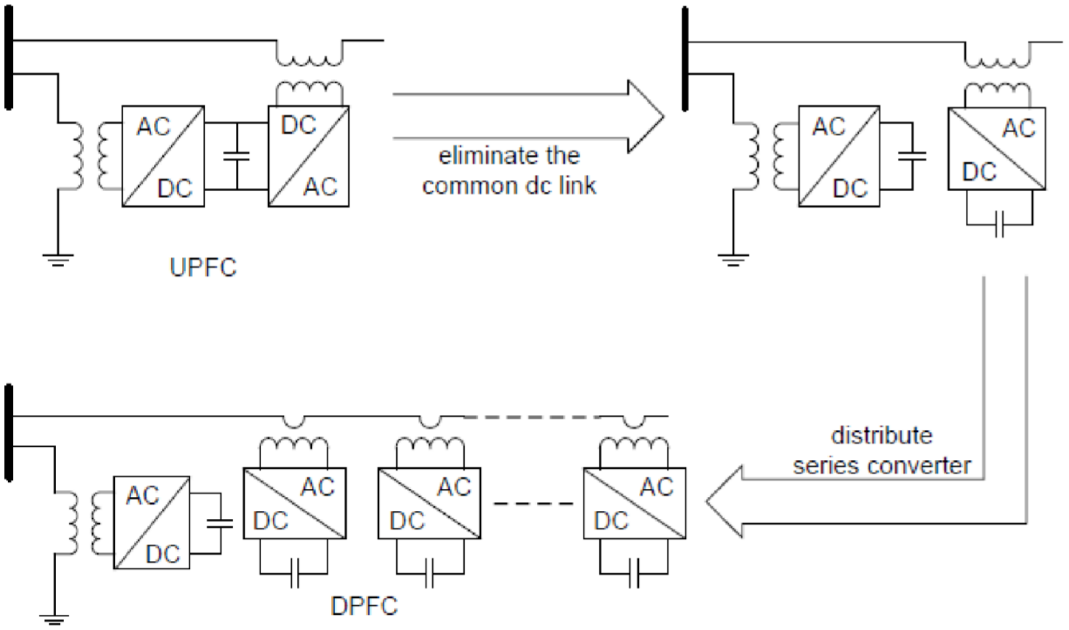

Figure 3.5 Flowchart from UPFC to DPFC

As shown, additional the key components shunt and series converters, a DPFC additionally needs a high pass filter that's shunt connected to the opposite fact of the cable and a Y-delta electrical device on either side of the road. The explanation for these further parts is explained later. The exclusive management capability of the UPFC is given by the succeeding affiliation between the shunt and series converters that permits the active power to freely exchange.

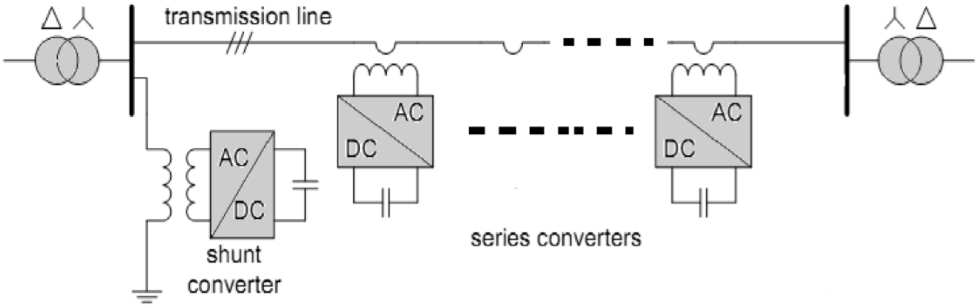

Figure 3.6 DPFC structure

3.3.2 DPFC CONTROL

To control the multiple converters, DPFC consists of three types of controllers; they are central controller, shunt control, and series control, as shown in Fig.7. The shunt and series control are local controllers and are responsible for maintaining their own converters' parameters. The central control takes account of the DPFC functions at the power-system level. The function of each controller is listed next.

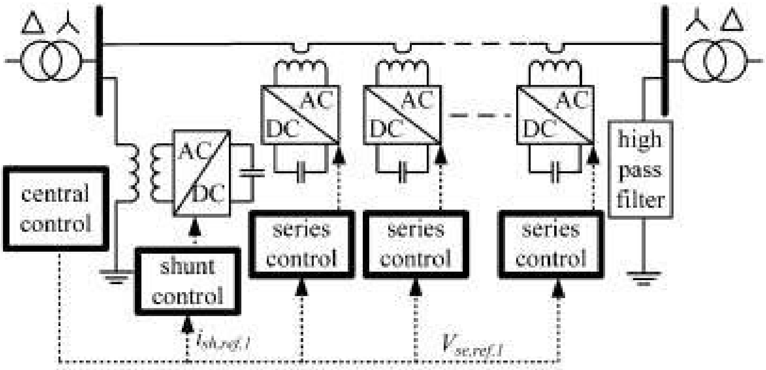

Figure 3.7 DPFC control block diagram

A. Central Control

The central control generates the reference signals for both the shunt and series converters of the DPFC. It is focused on the DPFC tasks at the power-system level, such as power-flow control, low-frequency power oscillation damping, and balancing of asymmetrical components. According to the system requirement, 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 are at the fundamental frequency.

B. 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 the third-harmonic frequency components and to generate series voltage at the fundamental frequency that is prescribed by the central control. The third-harmonic frequency control is the major control loop with the DPFC series converter control. The principle of the vector control is used here for the dc-voltage control [10]. The third-harmonic current through the line is selected as the rotation reference frame for the single-phase park transformation, because it is easy to be captured by the phase-locked loop (PLL) [11] in the series converter. As the line current contains two frequency components, a third high-pass filter is needed to reduce the fundamental current. The d-component of the third harmonic voltage is the parameter that is used to control the dc voltage, and its reference signal is generated by the dc-voltage control loop. To minimize the reactive power that is caused by the third harmonic, the series converter is controlled as a resistance at the third-harmonic frequency. The q component of the third-harmonic voltage is kept zero during the operation. As the series converter is single phase, there will be voltage ripple at the dc side of each converter. The frequency of the ripple depends on the frequency of the current that flows through the converter [12], [13]. There are two possible ways to reduce this ripple. One is to increase the turn ratio of the single-phase transformer of the series converter to reduce the magnitude of the current that flows into the converter. The other way is to use the dc capacitor with a larger capacitance.

C. Shunt Control

The block diagram of the shunt converter control is shown in Fig.9. The objective of the shunt control is to inject a constant third harmonic current into the line to provide active power for the series converters. The third-harmonic current is locked with the bus voltage at the fundamental frequency. A PLL is used to capture the bus-voltage frequency, and the output phase signal of the PLL is multiplied by three to create a virtual rotation reference frame for the third harmonic component. The shunt converter's fundamental frequency control aims to inject a controllable reactive current to grid and to keep the capacitor dc voltage at a constant level. The control for the fundamental frequency components consists of two cascaded controllers. The current control is thinner control loop, which is to modulate the shunt current at the fundamental frequency. The q component of the reference signal of the shunt converter is obtained from the central controller, and d-component is generated by the dc control.

3.3.3 Advantages of DPFC

The DPFC can be considered a UPFC that employs the D-FACTS concept and the of exchanging power through the third harmonic. In this way, the DPFC has some basic advantage and application such as:

- **High controllability**: the DPFC can simultaneously control all the parameters of the transmission network line impedance, transmission angle and bus voltage.
- **High reliability**: the redundancy of the series converter gives high reliability with-out increasing cost. In addition, the shunt and series converters are independent and failure of one will not influence the other converters.
- **Low cost**: There is no part to voltage isolation needed between the series converters of various phases. The ability rating of every device is additionally low result of the massive variety of the series converters they will be factory-made nonparallel production. If the ability system is already equipped with the STATCOM, the system will be updated to the DPFC with solely low further price.

3.4 Using third harmonic controller

Due to the distinctive options of third harmonic frequency parts during a three-phase system, the third harmonic is chosen for active power exchange within the DPFC. During a three phase system the third harmonic in every part is identical, which suggests they are zero sequence parts. Since the zero sequence harmonic will be clearly blocked by Y–Δ transformers and these are extensively incorporated in power systems (as a way of fixing voltage), there is no further filter needed to inhibit harmonic run. Harmonics interfere with sensitive type of electronic communication and networks. Low order third harmonics causes hot neutrals, grounding potential rise (GPR), light-weight unsteady, malfunction of processed processing equipment and computer networks and computer equipment. There is a unit many outlined measures generally used for indicating the harmonic severity and content of a wave. One amongst the foremost common measures is that the total harmonic distortion in current (THD).

THD = [redacted]……………………………3.2

Where I_n: Fundamental (50Hz) Current; n: Harmonic order and I_1: Harmonic current.

3.5 DPFC Model

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.

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 3^{rd} harmonic component of a three phase system can be considered a single-phase component, as its components are all in phase ('zero-sequence'). In this section, the network modeling is introduced, followed by the modeling of the DPFC converter. Once the separated models are presented, the correlation between the different models is given.

3.5.1 Network Modeling

This section presents the mathematical representation of a network with a DPFC at both the fundamental and the 3^{rd} harmonic frequencies.

3.5.2 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. As mentioned before, the switching behavior of the converter is not considered. To simplify the analysis, the loss of the converter is neglected.

Due to the identity of the series converters,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 if necessary. The AC side and the DC side voltages of the series converter are V_{se} and $V_{se,DC}$ respectively and $ref_{V,sef}$ is the modulation amplitude of the reference AC signal in pu, which is generated by the series control. Note that the AC voltages and currents consist of two components at different frequencies, namely the fundamental and the 3^{rd} harmonic frequency components that are denoted by subscripts 1 and 3 respectively. Their relationship can be illustrated as follows:

$$Vse = Vse,1 + Vse,3 \qquad (3.2)$$

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}:

$$Vse = refV,se \cdot Vse,dc \qquad (3.3)$$

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:

$$\begin{bmatrix} V_{se,1} \\ V_{se,3} \end{bmatrix} = \begin{bmatrix} ref_{V,se,1} \\ ref_{V,se,3} \end{bmatrix} \cdot V_{se,dc} \qquad (3.4)$$

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:

$$C_{se}\frac{dV_{dc,se}}{dt} = I_{dc,se} \qquad (3.5)$$

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

$$C_{se}\frac{dV_{dc,se}}{dt} = (ref_{V,se,1} + ref_{V,se,3})(I_1 + I_3) \qquad (3.6)$$

Series converter model

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

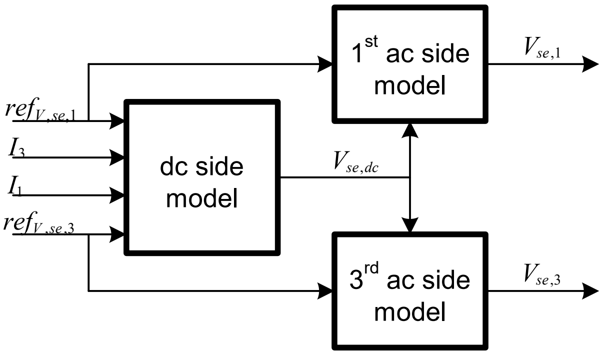

Figure 3.8 Block diagram of the series converter model

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.

3.5.3 Shunt Converter Modeling

The shunt converter consists of a three-phase converter that is back-to-back connected to a single-phase 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 grid. The single-phase converter is connected between the ground and the neutral point of the Y-Δ transformer to inject 3^{rd} harmonic current. The simplified diagram of the shunt converter is shown Figure.

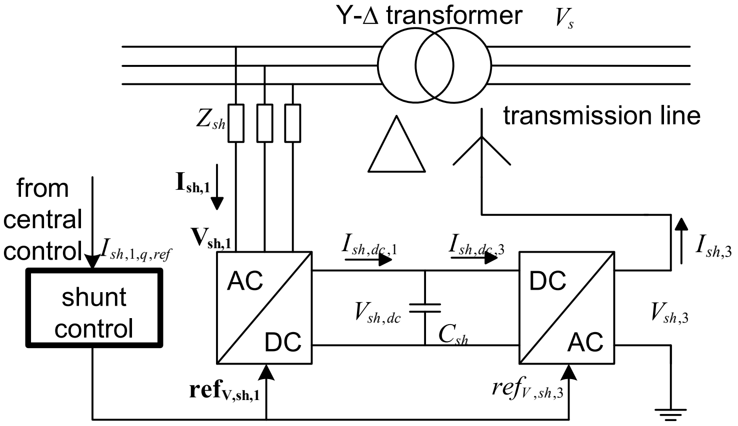

Figure 3.9 Simplified diagram of the shunt converter

Due to no 3^{rd} 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 **Vsh,1** and the current **$I_{sh,1}$**. The voltage $V_{sh,3}$ and current $I_{sh,3}$ at the 3^{rd} harmonic frequency are single-phase components.

AC side modeling

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

$$V_{sh,1} = ref_{V,sh,1} \cdot V_{sh,dc} \qquad (3.7)$$

$$V_{sh,3} = ref_{V,sh,3} \cdot V_{sh,dc}$$

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:

$$C_{sh}\frac{dV_{sh,dc}}{dt} = I_{sh,dc,1} - I_{sh,dc.3} \qquad (3.8)$$

3.6 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 [Kann 04, Papi 97] is employed to control the DPFC converter. The calculation of the controller parameter is based on the Internal Model Control (IMC) method.

3.6.1 Series Converter Control

Each DPFC series converter is locally controlled by its own controller, and the scheme for each series control is identical. To control the series converter, separate control loops are employed for the two frequency components. The 3^{rd} harmonic control loop is used for DC voltage control. The block diagram of the DPFC series converter control is shown in Figure 3-10.

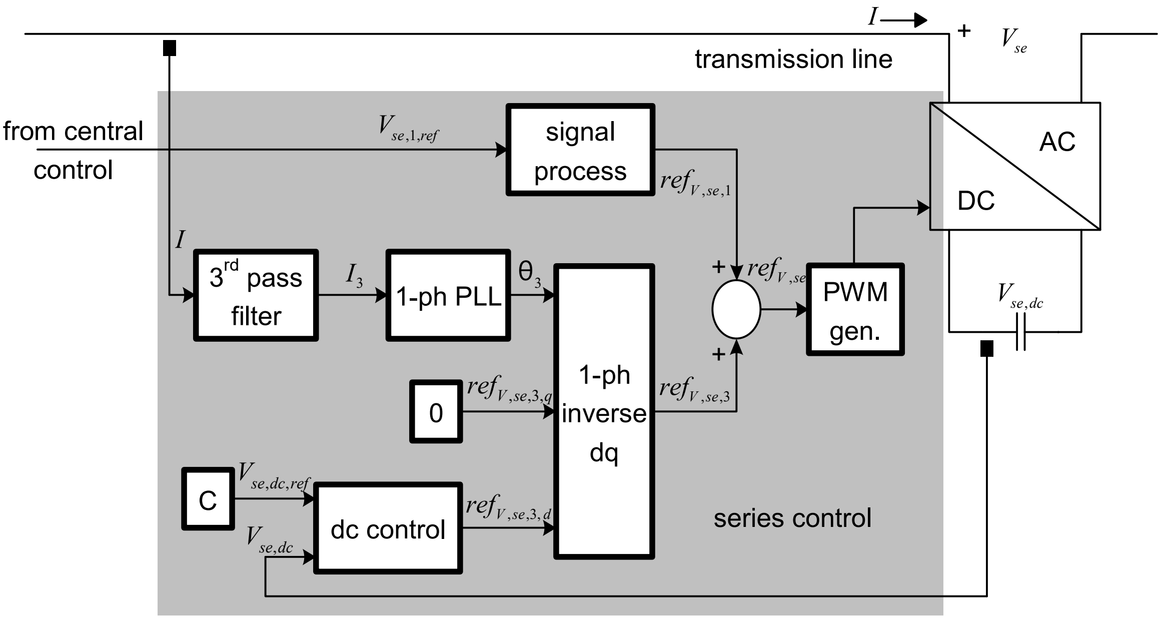

Figure 3.10 Control scheme of the series converter

Control of the fundamental frequency component

The reference voltage at the fundamental frequency for the series converters is generated by the central control and transmitted to each converter through a communication channel. The signal-process block is utilized to transform the ‘communication voltage’ to the AC reference voltage at the fundamental frequency. This AC signal, superimposed with the signal generated by the 3^{rd} harmonic control, is sent to the PWM generator to drive the switches of the series converter.

Control of the third harmonic frequency component

The 3^{rd} harmonic frequency control is the major control loop with the DPFC series converter control. Its task is to maintain the DC capacitor voltage.

The principle of vector control is used here for DC voltage control. Normally, the voltage is used as the rotation reference frame for Park’s transformation, but here the 3^{rd} harmonic current through the line is selected because it is easily measured by the series converter. As the line current contains two frequency components, a 3^{rd} band pass filter is needed to extract the 3^{rd} harmonic current. The single-phase Phase-Lock-Loop (PLL), as described in Appendix B, creates a rotation reference frame from the 3^{rd} harmonic current. The d component of the 3^{rd} harmonic voltage is the parameter used to control the DC voltage. The control signal is generated by the DC voltage control loop. Because the q component of the 3^{rd} harmonic voltage will only cause reactive power injection to the AC network, the q component is kept at zero during the operation.

- 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 can be written as:

$$C_{se}\frac{dV_{se,dc}}{dt} = \frac{1}{2}\left(ref_{V,se,1,d}I_{1,d} + ref_{V,se,3,d}I_{3,d}\right) \tag{3.9}$$

As shown, the DC capacitor voltage is affected by both the fundamental and the 3^{rd} 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 3^{rd} harmonic current within the line is a constant value, the current $I_{3,d}$ is considered constant.

To design the controller, is transformed from 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:

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 [Pete 05] as a part of the DC voltage control loop. The scheme of the DC voltage control is shown in Figure 3.11

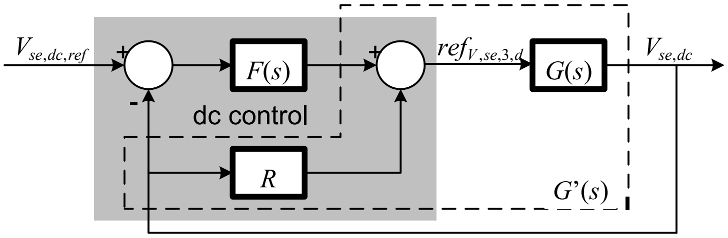

Figure 3.11 Scheme of the DC voltage control loop of the series converter

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:

$$G'(s) = \frac{G(s)}{1 + RG(s)} = \frac{I_{3,d}}{2sC_{se} + RI_{3,d}} \quad (3\ .10)$$

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:

$$F(s) = \frac{\alpha_d}{s} G'(s)^{-1} \quad (3.11)$$

where α_d is a design parameter, and means the desired bandwidth of the closed-loop system here. The relationship between the bandwidth and the rise time t_{rise} (from 10 % to 90% of the final value) is [Otte 03]:

$$\alpha_d = \frac{\ln 9}{t_{rise}} \quad (3.12)$$

Consequently, $F(s)$ is a PI controller and can be described by:

$$F(s) = \frac{2C\alpha_d}{I_{3,d}} + \frac{R\alpha_d}{s} \qquad (3.13)$$

To calculate the active damping R, a suitable choice is to make the inner feedback loop as fast as the closed-loop system. This means placing the pole of $G'(s)$ at $-\alpha_d$, thereby obtaining the active damping R:

$$\frac{RI_{3,d}}{2C} = \alpha_d \Rightarrow R = \frac{2C\alpha_d}{I_{3,d}} \qquad (3.14)$$

Accordingly, the parameters of PI controllers k_p and k_i and the active damping R within the DC voltage control can be calculated from the following equations:

$$k_p = \frac{2C\alpha_d}{I_{3,d}}, \quad k_i = \frac{2C\alpha_d^2}{I_{3,d}}, \quad R = \frac{2C\alpha_d}{I_{3,d}} \qquad (3.15)$$

3.6.2 Shunt Converter Control

The shunt converter contains two converters as described. The single phase converter injects the constant 3^{rd} harmonic current into the grid. The three-phase converter maintains the DC voltage at a constant value and generates reactive power to the grid. The control of each converter is independent. A block diagram of the shunt converter control.

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 3^{rd} harmonic current into the grid, therefore requiring a current controller. The 3^{rd} harmonic current is locked with the bus voltage at the fundamental frequency. A PLL is used to capture the bus voltage frequency, and the output signal of the PLL θ_1 is multiplied by 3 to create a virtual rotation reference frame for the 3^{rd} harmonic component.

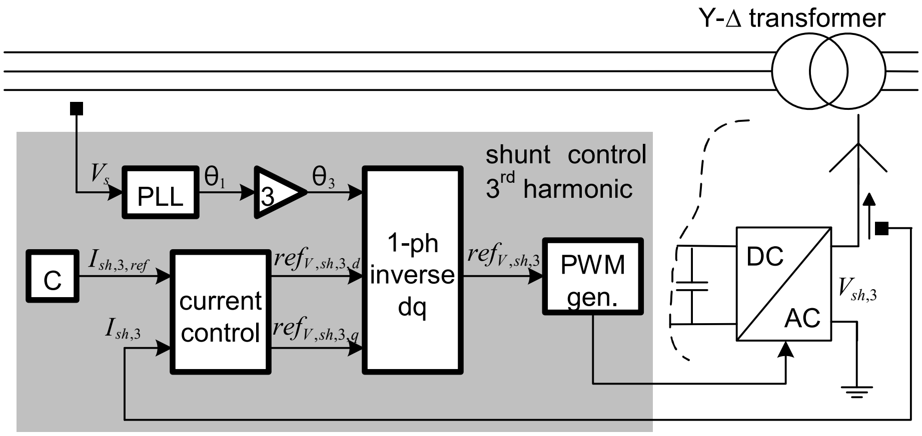

Figure 3.12: Control scheme of the shunt converter: for the 3rd harmonic frequency components

3.4 Single Inverter Circuit modeling

Static (or solid-state) inverters are used in many electrical energy sources requiring a DC-to-AC transformation as well as in power interfacing. In Single phase applications, the full-bridge and half-bridge inverters represent the basic circuit topologies, while multilevel inverters and Z-inverters represent a further development approach retaining the fundamental inverter circuit methodology. Different circuit design approaches address various issues that may be more or less important depending on the way the inverter is intended to be used. In some cases, the development of the inverter involves changes to the switching gate-drive algorithm, example pulse-width modulation (PWM), sinusoidal pulse-width modulation (SPWM), and space-vector pulse-width modulation (SVPWM) in addition to developments of the inverter controller.

The inverter output voltage can be either +Vdc, -Vdc or zero, depending on how the inverter switches are controlled. The inverter controller operates so as to create an AC output voltage by generating an appropriate inverter switching sequence.

The basic circuit of a single-phase half-bridge inverter, which is used for converting a DC voltage to an AC voltage, is shown in Figure 3.13

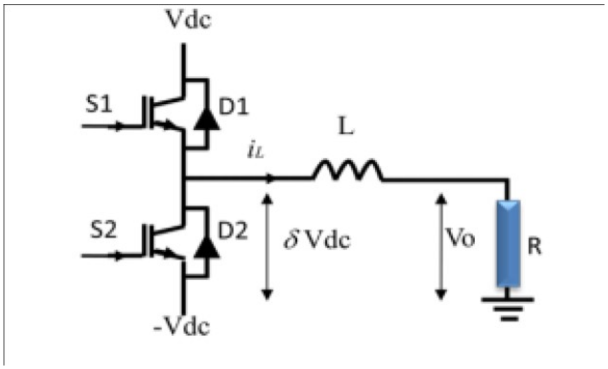

Figure 3.13 single phase inverter circuit

This type of inverter operates from a positive and a negative DC source and produces AC voltage. The switching transistor S1 is driven complementary to switching transistor S2. The transistor S1 conducts during the first sub-interval

0 <t<(where the inverter switching period) while S2 conducts during the complementary sub-interval $\delta Tsw < t < Tsw$. The volt-second balance across the inductor is given.

$$L\frac{di_L}{dt} = V_o - V_{dc}(2\,\delta - 1)$$

CHAPTER FOUR

4 DPFC Modelling and Simulink Results

The whole model of system under study is shown in Fig.4.1. The DPFC is placed in transmission line, which the shunt converter is connected to the transmission line in parallel through a Y-Δ three phase transformer, and series converters is distributed through this line. The system parameters are listed in appendix TABLE 4.1. To simulate the dynamic performance, a three phase fault is considered near the load.

4.1 DPFC Modelling

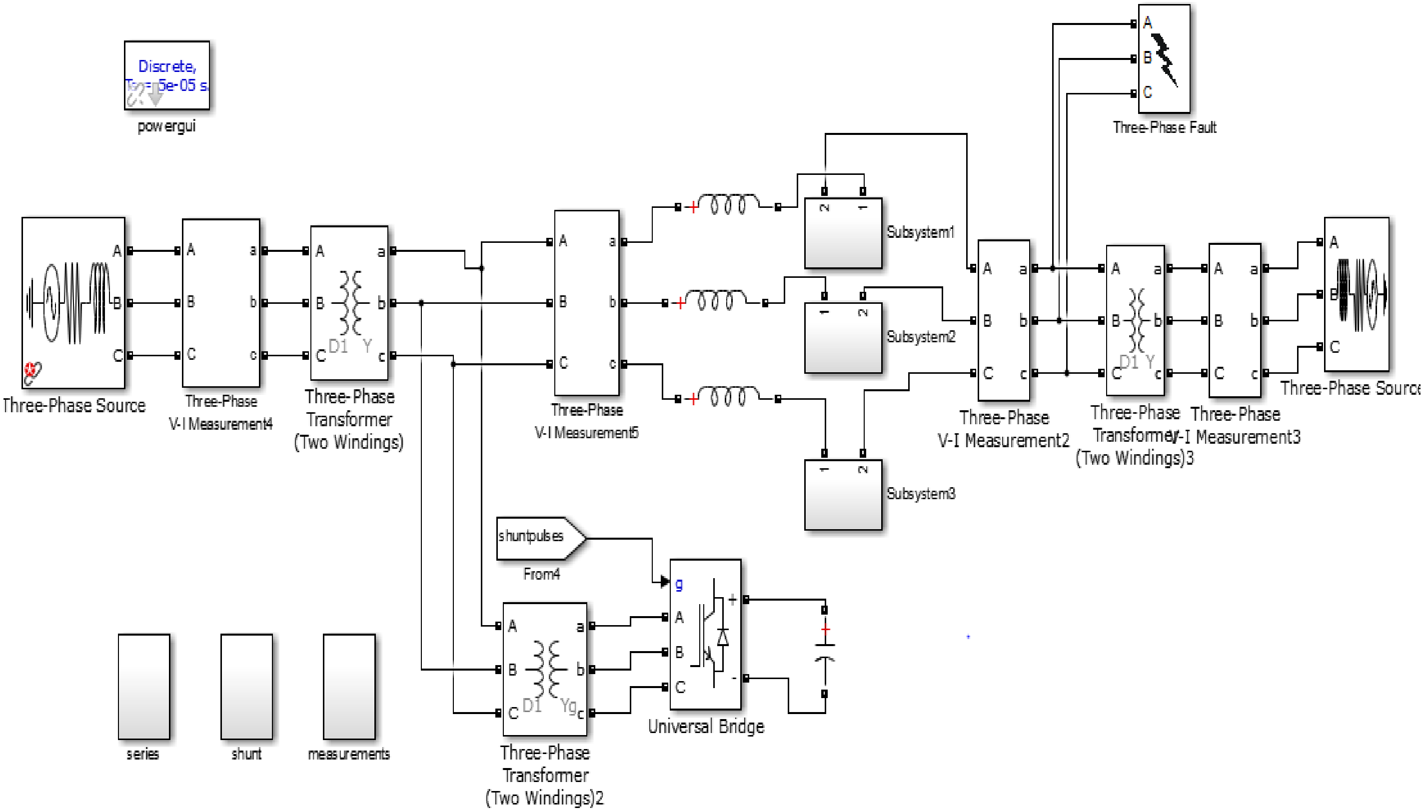

Figure 4.1 Matlab Model of DPFC

4.2 Series Converter SIMULINK Model

Within the setup, multiple series converters are controlled by a central controller. The central controller gives the reference voltage signals for all series converters. The voltages and current within the setup are measured by its simulink outputs.

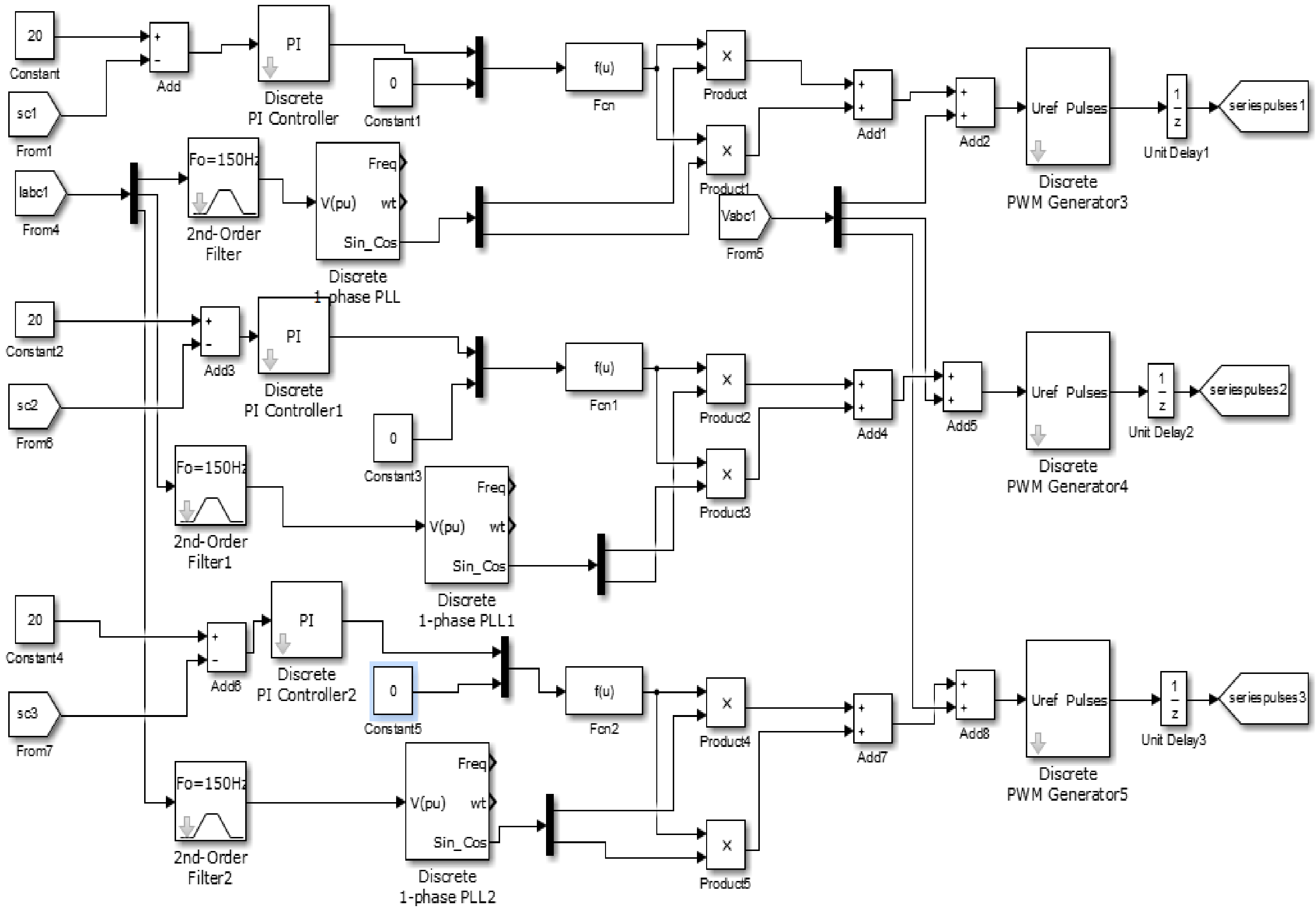

Fig.4.2 Simulated model for series converter

4.3 Shunt Converter SIMULINK Model

The basic function of the shunt converter is to supply or absorb the active power demanded by the series converter. The shunt converter controls the voltage of the DC capacitor by absorbing or generating active power from the bus, therefore it acts as a synchronous source in parallel with the system. To verify the DPFC principle, two situations are demonstrated: the DPFC behavior in steady state and the step response. The voltage injected by the series converter, the current through the line, and the voltage and current at the Δ side of the transformer.

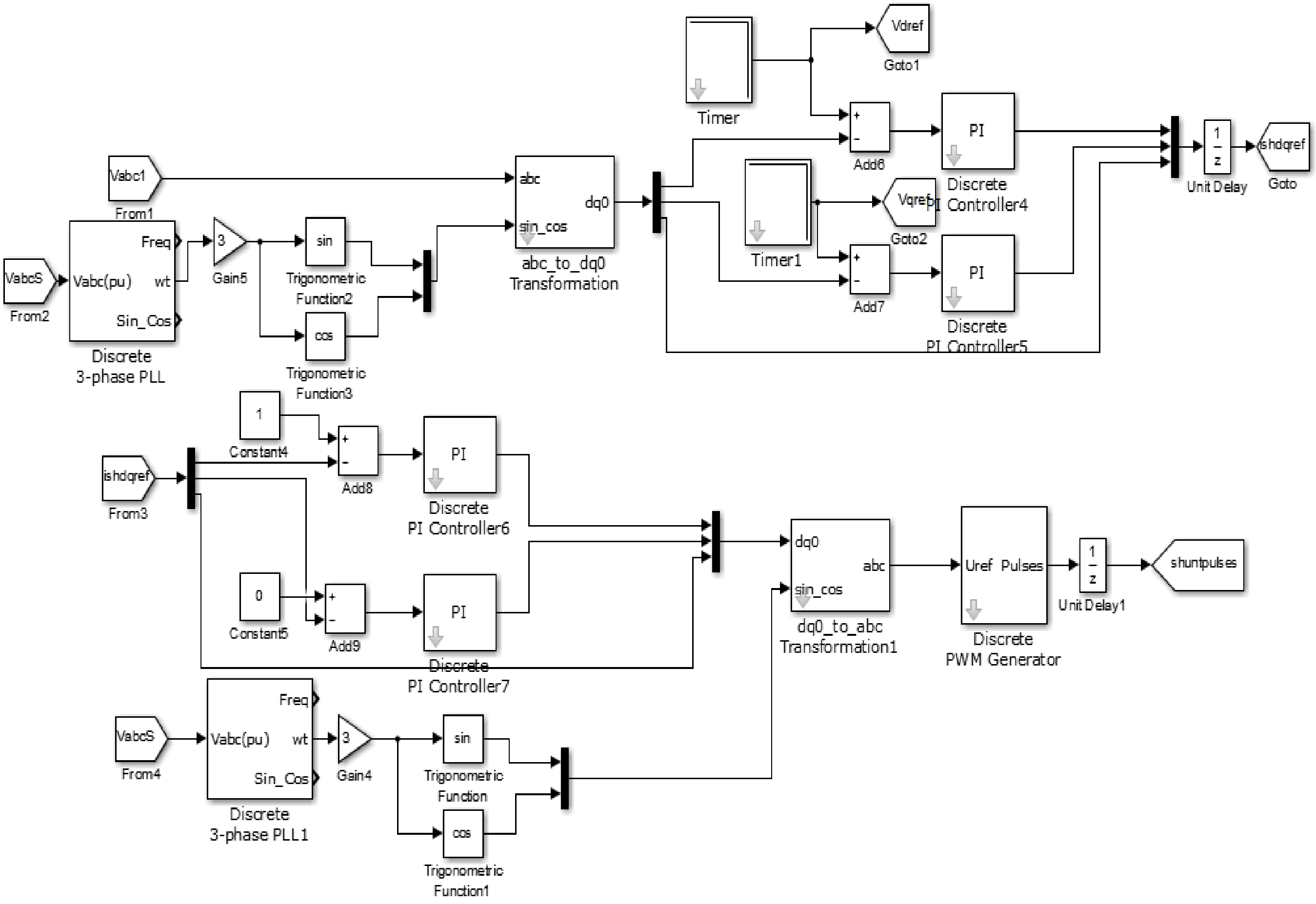

Fig.4.3 Simulated model for shunt converter

Table 4.1 Simulation System Parameters

Parameters	Value
Three phase source	
Rated Voltage	230 KV
Rated Power/Frequency	100 MW/60HZ
X/R	3
Short Circuit Capacity	11000 MW
Transmission Line	
Resistance	0.012 pu/km
Inductance/Capacitance Reactance	0.12/0.12 pu/km
Length of transmission line	100 km
Shunt Converter 3-phase	
Nominal Power	60 MVAR
DC link Capacitor	600µF
Coupling Transformer(shunt)	
Nominal power	100 MVA
Rated Voltage	230KV
Series Converter	
Nominal Power	6 MVAR
Rated Voltage	6 KV
Three-Phase fault	
Type	ABC-G
Ground resistance	0.01 ohm

4.4 SIMULATION RESULTS

To verify the principle and control of the DPFC, one shunt converter and three single phase series converters the design was simulated to predict the steady state performance. A prototype based on proposed topology is simulated using MATLAB/SIMULATION. Therefore, two situations are demonstrated: the DPFC behaviour in steady state and the step response. In steady state, the series converter is controlled to insert a voltage vector with both d- and q-component. The DPFC controls the power flow through transmission lines by varying the voltage injected by the series converter at the fundamental frequency. Illustrates the simulation results of step response. A step change of the fundamental reference voltage of the series converter is made, which consists of both active and reactive variations, as shown in Fig.

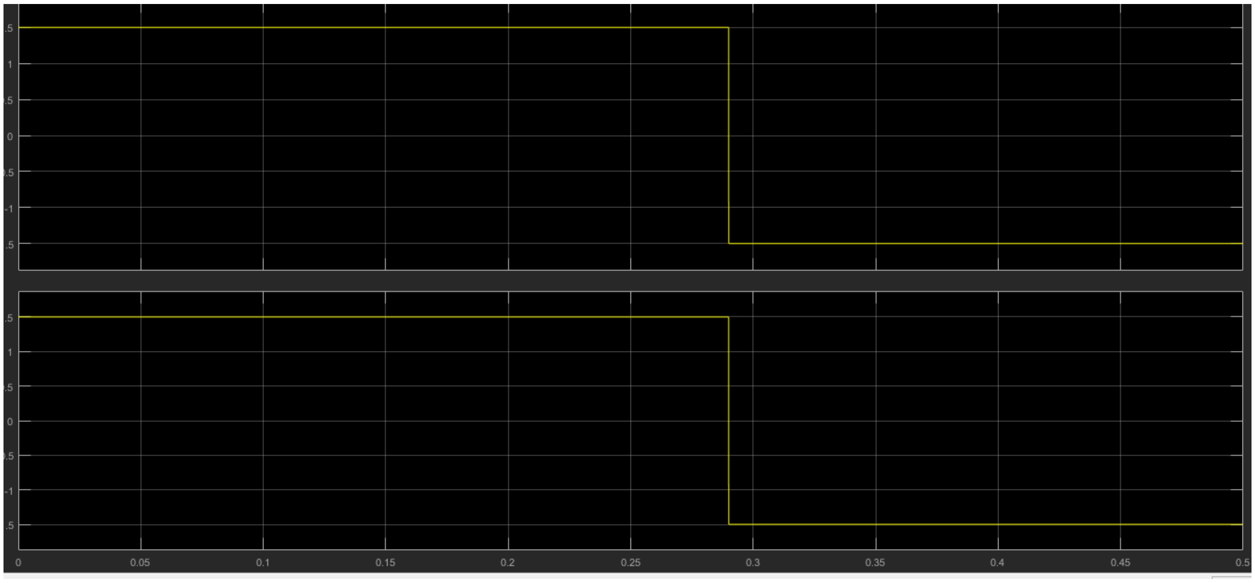

Figure 4.4 Reference voltage for the series converters

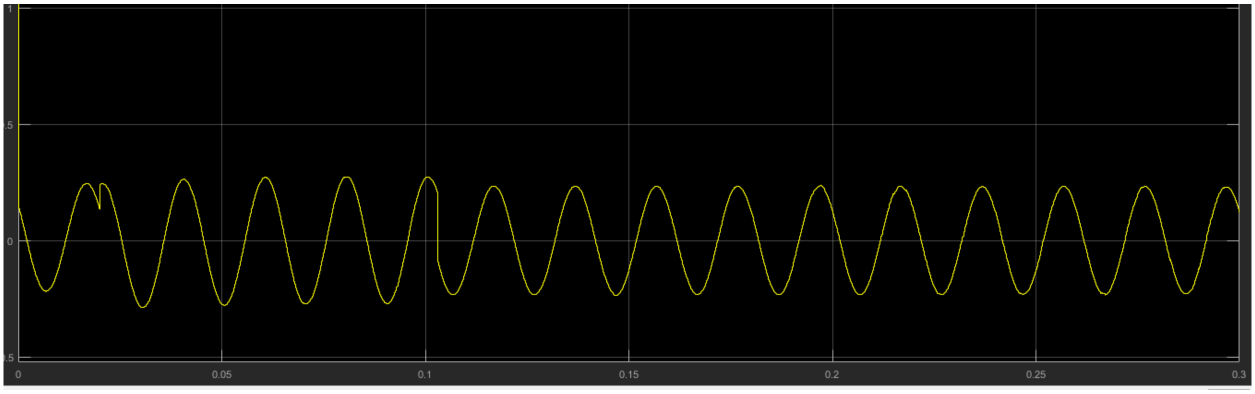

Figure 4.5 Step response of the DPFC: line current

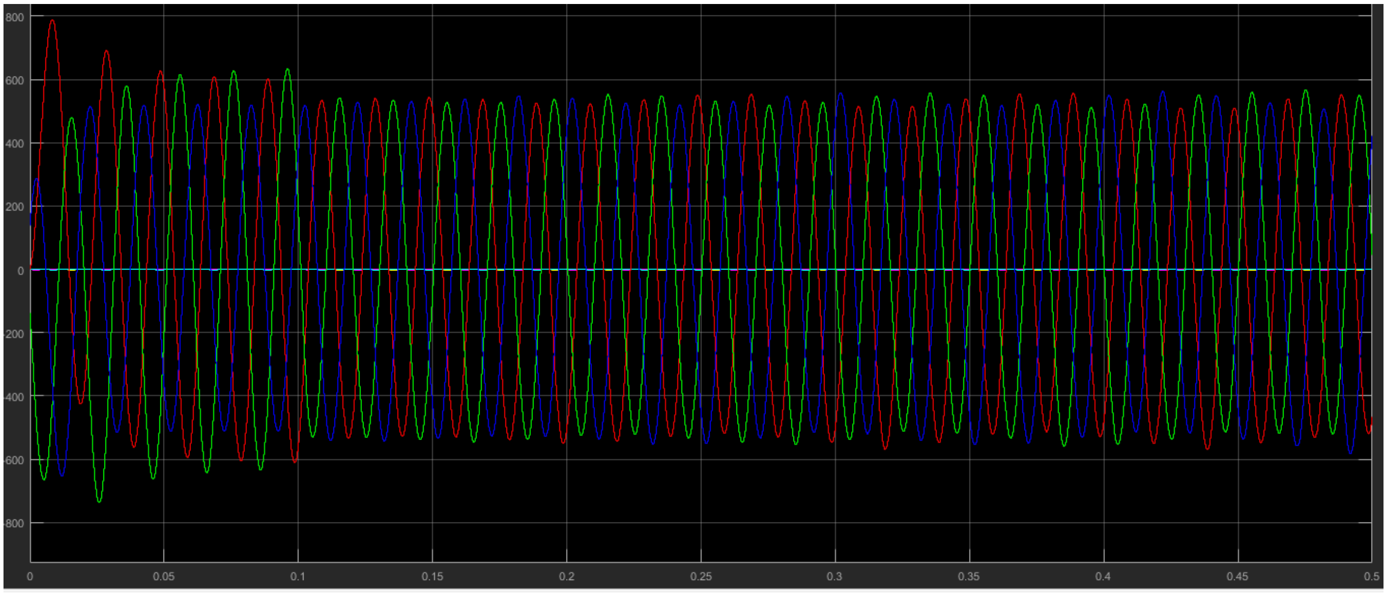

Figure 4.6 Step response of the DPFC: bus voltage and current at the Δ side of the transformer.

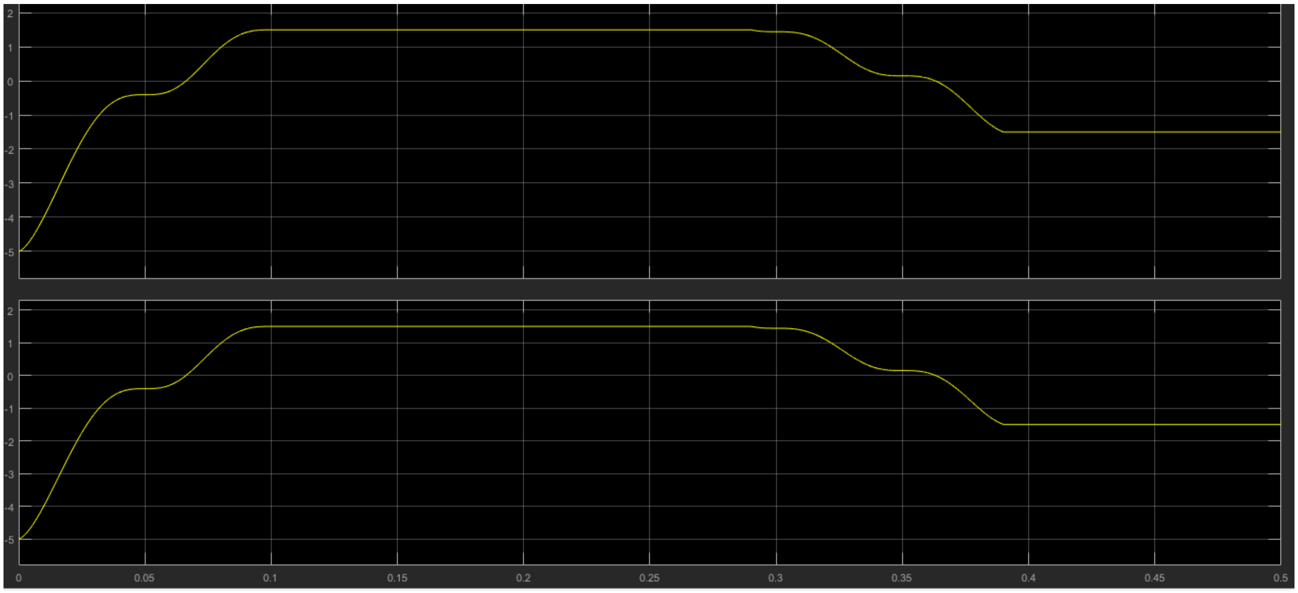

Figure 4.7 Step response of the DPFC: active and reactive power injected by the series converter at the fundamental frequency

CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATION

5.1 CONCULUSION

This paper presents the new concept of DPFC system and the method of transmitting active power through the same line at different frequency. The distributed converters bring the following benefits: reduce cost for both equipment and maintenance; increase the reliability of the whole system, even when the shunt converter breaks, series converters can also work as variable conductor; break the location constrain, the converters are physical separated without losing control capability. Since the exchange active power is through the same line which transmits the fundamental power, the transmission capability of t line will be reduced.

5.2 RECOMMENDATIONS

The thesis shows that the DPFC has a lower cost and should be more reliable than the UPFC. However, the DPFC also brings about some new problems. The issues that should be addressed by future research are:

- **Communications**: Because the series converters operate outdoors, the communication (wireless or PLC) between the central control and series converters is susceptible to disturbances, such as lighting or a geomagnetic storm. Accordingly, the communication should be reliable enough to continue operating in spite of these disturbances.
- **Weight reduction of the series converter**: Since the series converters are hung on transmission lines, they result in extra pressure for towers. A lightweight series converter unit is desirable. The problem created by the DPFC, which cannot be avoided but can be minimized by future research is:
- **3rd harmonic current management**: The 3rd harmonic components within the DPFC lead to extra losses in transmission lines and transformers. In this thesis, the 3rd harmonic current within the DPFC is set at a constant value. The magnitude of the 3rd harmonic current can be managed in a way that it is adjusted according to the requirement for active power. Consequently, the loss of the DPFC can be reduced. Besides the above concerns, additional DPFC applications for utility grid are also interesting for future research: Centralized control for multiple DPFC: As the DPFC series converter can be easily applied to multiple lines, the centralized control of multiple DPFCs is an interesting potential application.

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