UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

IMPLEMENTATION AND PERFORMANCE EVALUATION OF DISTRIBUTED POWER FLOW CONTROLLER (DPFC) TO IMPROVE POWER QUALITY IN POWER TRANSMISSION SYSTEM

MASTER THESIS

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ELECTRICAL AND ELECTRONICS ENGINEERING DEPARTMENT

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Thesis Supervisor: Prof. Dr. Doğan ÇALIKOĞLU

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UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

I hereby declare that all the information in this study I presented as my Master's Thesis, called "Implementation and Performance Evaluation of Distributed Power Flow Controller (DPFC) to Improve Power Quality in Power Transmission System" has been presented in accordance with the academic rules and ethical conduct. I also declare and certify on my honor that I have fully cited and referenced all the sources I made use of in this present study.

Ali, Al-HARDANEE
27.11.2017

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In the name of ALLAH, the most Gracious, the Most Merciful for giving me the strength to complete this work in its final form. My Lord mercy and peace be upon our leader MOHAMMED peace be upon on him, who invites us to science and wisdom, and members of his family and his followers.

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LIST OF ABBREVIATIONS

Pq : Power quality

Facts : Flexible alternating current transmission system

Dpfc : Distributed power flow controller

Upfc : Unified power flow controller

Svc : Static var compensator

Thd : Total harmonic distortion

Statcom : Static synchronous compensator

Sssc : Synchronous Series Compensator Controller

C_{se} : Capacitor connected to series converter

C_{sh} : Capacitor connected to shunt converter

I : Line Current

I* : Conjugate of line current

I_r : Receiving end current

I_{sh} : Shunt current

I_A : Current through phase A

I_B : Current through phase B

I_C : Current through phase C

I_i : i^{th} harmonic current

L : Inductance of the transmission line per phase

L_3 : Equivalent Inductance of the transmission line per phase 3rd harmonic frequency

P_r : Active power at the receiving end of compensated line

P_{ro} : Active power at the receiving end

$P_{se,1}$: Active power exchanged by series converter at fundamental frequency

$P_{se,3}$: Active power exchanged by series converter at 3rd harmonic frequency

$P_{sh,1}$: Active power exchanged by shunt converter at fundamental frequency

$P_{sh,3}$: Active power exchanged by shunt converter at 3rd harmonic frequency

$P_{r,c}$: Active power control range of DPFC

Q_r : Reactive power at the receiving end of compensated line

Q_{ro} : Reactive power at the receiving end

$Q_{se,1}$: Reactive power exchanged at fundamental harmonic frequency

$Q_{se,3}$: Reactive power exchanged by series converter at 3rd harmonic frequency

$Q_{r,c}$: Reactive power control range of DPFC

R : Resistance of the transmission line per phase

R_3 : Equivalent resistance of the transmission line per phase at 3rd harmonic frequency

$ref_{v,se}$: Reference input to series converter

$ref_{v,se,1}$: Reference input to series converter at fundamental frequency

$ref_{v,se,3}$: Reference input to series converter at 3rd harmonic frequency

$ref_{v,se,1,d}$: d-axis component of reference input to series converter at fundamental frequency

$\mathbf{ref_{v,se,1,q}}$: q-axis component of reference input to series converter at fundamental frequency

$\mathbf{ref_{v,se,3,d}}$: d-axis component of reference input to series converter at 3rd harmonic frequency

$\mathbf{ref_{v,se,3,q}}$: q-axis component of reference input to series converter at 3rd harmonic frequency

$\mathbf{ref_{v,sh}}$: Reference input to shunt converter

$\mathbf{ref_{v,sh,1}}$: Reference input to shunt converter at fundamental frequency

$\mathbf{ref_{v,sh,3}}$: Reference input to shunt converter at 3rd harmonic frequency

$\mathbf{ref_{v,sh,1,d}}$: d-axis component of reference input to shunt converter at fundamental frequency

$\mathbf{ref_{v,sh,1,q}}$: q-axis component of reference input to shunt converter at fundamental frequency

$\mathbf{ref_{v,sh,3,d}}$: d-axis component of reference input to shunt converter at 3rd harmonic frequency

$\mathbf{ref_{v,sh,3,q}}$: q-axis component of reference input to shunt converter at 3rd harmonic frequency

$\mathbf{S_r}$: Apparent power in compensated network

$\mathbf{S_{ro}}$: Apparent power in uncompensated network

$\mathbf{S_{r,c}}$: Control range of DPFC

$\mathbf{V_s}$: Sending end bus voltage

$\mathbf{V_r}$: Receiving end bus voltage

$\mathbf{V_{DC}}$: DC voltage of the converter

$\mathbf{V_{se}}$: Series converter voltage

$\mathbf{V_i}$: ith harmonic voltage

$\mathbf{V_{sh,1}}$: Shunt voltage at fundamental frequency

$\mathbf{V_{sh,3}}$: Shunt voltage at 3rd harmonic voltage

$\mathbf{V_{se,1,ref}}$: Fundamental reference voltage of series converter

$\mathbf{V_{sh,i}}$: Shunt voltage at ith harmonic frequency

$\mathbf{V_{se,i}}$: Series voltage at ith harmonic frequency

$\boldsymbol{\omega}$: Angular velocity

$\mathbf{X}$: Inductive impedance

$\mathbf{X_C}$: Capacitive reactance

$\mathbf{X_i}$: Reactance at ith harmonic voltage

$\mathbf{X_{sh,1}}$: Shunt converter reactance at fundamental frequency

$\mathbf{X_{sh,3}}$: Shunt converter reactance at 3rd harmonic frequency

$\mathbf{Z}$: Impedance of the transmission line

$\mathbf{Z_3}$: Impedance of the transmission line at 3rd harmonic frequency

$\boldsymbol{\theta}$: Transmission angle

$\boldsymbol{\delta}$: Phase angle of the impedance

$\mathbf{Ø_i}$: Phase angle between V_i and I_i

$\boldsymbol{\theta_3}$: Phase angle difference between the voltages $V_{sh,3}$ and $V_{se,3}$

$\boldsymbol{\alpha_d}$: Bandwidth of d-compoment

$\boldsymbol{\alpha_q}$: Bandwidth of q-compoment

ABSTRACT

IMPLEMENTATION AND PERFORMANCE EVALUATION OF DISTRIBUTED POWER FLOW CONTROLLER (DPFC) TO IMPROVE POWER QUALITY IN POWER TRANSMISSION SYSTEM

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The basic function of the electrical power system is to deliver electricity to the consumer efficiently. This system deals with the electric power from generation to consumption passing through transmission and distribution. The rate of the electrical energy that is transferred within the transmission lines of the power system is known as ‘Power Flow’. For more clarity, it is the amount of active and reactive power that flows in the power transmission lines. When there is a problem with the power flow it causes a problem in the electrical power quality. For this reason, there is a great need to control the power flow in the transmission lines in order to avoid overloading.

The main objective of this study is to evaluate the performance for one of flexible AC transmission system (FACTS) devices which is used to control power flow through transmission system and to solve the power quality problems. This device called Distributed Power Flow Controller (DPFC). It is one of the best devices which is used to control power flow and to improve electrical power quality.

This device is developed and introduced recently as a power flow controller instrument inside the FACTS family devices. The use of DPFC offers higher reliability and lower cost than the others facts devices. DPFC is derived from UPFC and it has the capability at the same time to regulate all power system parameters such as transmission angle, the line impedances and the bus voltage magnitude. The performance evaluation of DPFC to control power system flow and to improve power quality is demonstrated in MATLAB/ SIMULINK through simulation at different operating conditions.

Keywords: Distributed Power Flow Controller, Power Quality, Power Flow Control, Facts Devices, Voltage Sag, Current Swell.

ÖZET

GÜÇ İLETİM SİSTEMİNDE GÜÇ KALİTESİNİ GELİŞTİRMEK İÇİN DAĞITIM GÜCÜ AKIMI KONTROLÖRÜNÜN (DPFC) UYGULAMA VE PERFORMANS DEĞERLENDİRMESİ

AL-HARDANEE, Ali Mohammed
Yüksek Lisans, Elektrik ve Elektronik Mühendisliği Bölümü
Tez Danışmanı: Prof. Dr. Doğan ÇALIKOĞLU
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Elektrik güç sisteminin temel işlevi, tüketiciye verimli bir şekilde elektrik iletmektir. Bu sistem, jeneratörden, tüketime, iletim ve dağıtım yoluyla geçen elektrik enerjisini ele alıyor. Güç sisteminin iletim hatlarında iletilen elektrik enerjisine oranı 'Güç Akışı' olarak bilinir. Bunun açıklaması; güç aktarma hatlarında akan aktif ve reaktif güç miktarıdır. Güç akışı ile ilgili bir problem olduğunda, elektriksel güç kalitesinde bir probleme neden olur. Bu nedenle aşırı yüklenmeyi önlemek için iletim hatlarındaki güç akışını kontrol etmek büyük bir ihtiyaçtır.

Bu çalışmanın temel amacı; iletim sisteminde güç akışını kontrol etmek ve güç kalitesi problemlerini çözmek için kullanılan, esnek AC iletim sistemi (FACTS) cihazlarından birinin performansını değerlendirmektir. Bu cihaz Güç Dağıtımı Akış Kontrol Cihazı (DPFC) olarak adlandırılır. Güç akışını kontrol etmek ve elektrik güç kalitesini artırmak için kullanılan en iyi cihazlardan biridir.

Bu cihaz son zamanlarda geliştirilmiş ve FACTS ailesi cihazları içinde bir güç akışı kontrol cihazı olarak yakın zamanda piyasaya sürülmüştür. DPFC'nin kullanımı diğer cihazların gerçek cihazlarından daha yüksek güvenilirlik ve daha düşük maliyet sunar. DPFC, UPFC'den türetilmiştir ve iletim açısı, hat direnci ve bara voltajı (gerilim) büyüklüğü gibi tüm güç sistemi parametrelerini düzenlemek için aynı anda kapasiteye sahiptir. Güç sisteminin akışını control etmek ve güç kalitesini artırmak için DPFC'nin performans değerlendirmesi, MATLAB / SIMULINK'de farklı çalışma koşullarında simülasyon yoluyla gösterilir.

Anahtar kelimeler: Güç Dağıtımı Akış Kontrol Cihazı, Güç Kalitesi, Güç Akışı Kontrolü, Gerçek Cihazlar, Gerilim Sarkması, Akım Şişmesi.

CHAPTER ONE

INTRODUCTION

1.1 Presentation of Work

The growth in the consumption of the electrical energy requires more transmission lines and more generation plants to support this growth. Sometimes, the transmission lines operate at higher rating than their design capacity and subjected to conditions cause disturbance of work. As a matter of fact, traditional solutions such as new transmission lines construction sometimes cannot be used for different reasons, such as the high cost and the lack of routes to these new transmission lines. However, within a power transmission network, many of parallel routes may exist from the electrical source to the loads. As the electrical power tends to flow through the route with the lowest impedance, this leads to overloaded transmission lines. Overloaded transmission lines make it difficult to exploit of full transmission capacity for transmission lines in the network. Consequently, to increase the transmission line capacity of the whole network, there is a need to shift the power from the overloaded line to other parallel paths. Also, when the transmission lines operate at higher rating than their design capacity, it will be subjected to conditions cause disturbance of work, this leads to major problems in the electrical power quality.

In the recent period, scientists and engineers have developed alternative solutions that are highly efficient and cost less. One of these solutions is the using of flexible AC transmission systems FACTS techniques which are characterized by their high efficiency to control the power system parameters and to improve the power quality of the electrical grid.

Custom power devices and FACTS devices are used in the electrical power system in transmission stage and distribution stage to control the power flow and to improve the electrical power quality. DVR, STATCOM/DSTATCOM, ACTIVE FILTERS, UPFC, UPQC, are some of the devices belong to the FACTS which used to improve the power quality of the voltage and the current. With the help of these devices, there capability to reduce the problems related to power quality [1].

To some extent, passive filters were used to mitigate reactive power disturbances and Harmonics, but there are many problems with them like size (they are large in size), the impact of source impedance on the efficiency and the problem of resonance. Active Power Filters APF are used for the power quality enhancement and for the power flow controlling. These filters can be classified according to the connecting configuration in the system. There are two types of Active power filters, series and shunt. Uniting both series APF& shunt APF we get a device identified as DPFC.

DPFC can eliminate the voltage and current based distortions together. A shunt APF eliminates all kinds of problems in current such as reactive power compensation, current harmonic compensation, power factor improvement. A series APF compensates voltage dip/rise so that the voltage at load side is perfectly regulated. The DPFC is a modern and sophisticated device, it is similar to the unified power flow controller UPFC in the structure. There are two main differences between UPFC and DPFC. The first one, is that in UPFC there is a common DC-link between the shunt and series converters, but in DPFC, this DC link is eliminated and in place of this DC link the transmission line is used to exchange the power between the series and the shunt converters and the second difference, is that UPFC has one three-phase series converter but the series converters in DPFC are single-phase and distributed through the line as a separated series converter [1].

1.2 Literature Survey

As the size, the load and the complexity of the power system networks increase, its performance will decrease. These factors lead to problems associated with power flow, power oscillations and voltage quality. Various studies have proposed resolutions for these problems, by means of the optimal place of FACTS and appropriate organization between FACTS controllers to amendment performance of the power systems. There is a massive amount of work reported in the literature in this area to improve power system performance. The FACTS technology has a group of controllers, that can be used individually or synchronized with other controllers connected to the network, thus allowing to gain better characteristics of the network's control.

Between the several facts devices presented for power system balance, the most comprehensive prominent device with very striking working features that stemmed from the facts family technology is the DPFC, which has ability to control independently and simultaneously both of active and reactive power flow in the transmission line systems, increase the power transfer capability of transmission lines and supply the most effective action in damping of low oscillations in frequency in multimachine power systems [2].

There are many studies that examine the problems and solutions to improve the quality of electrical power by using different techniques. The focus here will be on the studies that used the DPFC and proved excellent results.

Zhihui Yuan et al [3]. This study presented a new concept for power flow controller. This system is called the DPFC, this study presented the basic idea that proved to derive the DPFC from UPFC, the idea based mainly on using transmission line as the connection path between the AC port of shunt converter and series converters instead of joint DC link. This study improved that DPFC can do the same tasks as the UPFC at a lesser cost and higher efficiency.

Ahmad Jamshidi et al [4]. In this study, the device was applied to an electrical network with values similar to real values using the MATLAB environment at (230 kV, 100 MW, 60 Hz) system parameters. The Synchronous Reference Frame Method SRF is used as a way to calculate and get results. The results obtained proved the efficiency of the DPFC device in compensation of voltage sag and current swell.

P. RAMESH1 et al [5]. In this study, the steady-state response and control of power in the transmission line equipped with FACTS devices was presented. Simulations model for DPFC are carried out on two- machine systems with multi-series converters to display the control features of this device and their impact to increase power transfer capability and improve system reliability.

Mr. N. Peddaiah et al [6]. The system under study in this research paper was a single machine infinite-bus system. The result of this study discussed the performance of the system under fault effect without and with DPFC. It is shown that the DPFC can give a satisfactory performance in power quality mitigation and power flow controller.

Amin Safari et al [7]. This study present the modeling of current injection model for one of FACTS device based on distributed power flow controller in addition to current injection model of the DPFC for studying on the low-frequency oscillations is suggested to use for the first time and the design problem of the DPFC damping controller parameters are changed into an optimization problem which is resolved by a PSO technique that has a solid ability to find the most positive results.

Akhib Khan Bahamani et al [8]. In this study the model and Simulink of DPFC system were presented. Circuit models are advanced for two bus system without and with DPFC. The DPFC employs a shunt based Static Compensator STATCOM and multiple series converters to improve the power quality. DPFC has benefits like enhanced voltage shape and reduced power cost. The simulation results of two bus system with and without DPFC are presented in this study.

P.nirmala et al [9]. In this study SRF (synchronous reference frame method) is proposed to mitigate the voltage sags and find out the three single-phase reference voltages of DPFC. Submission of DPFC in power quality enrichment is simulated in MATLAB/Simulink program which displays the efficiency of the projected structure the gotten simulation results display the achievement of DPFC in power quality improvement, expressly in sag and swell mitigation.

1.3 Problem Formulation

To mitigate the problems and improve power flows in the power system we need to use an effective way with high performance and low cost. Between many devices that can be used in to give superior results, FACTS device DPFC has superior control capabilities and proved significantly raise in the transfer capacity and the utilization of the power system. DPFC is derived from UPFC by using transmission line to exchange active power instead of DC link between converters. The commercial success for UPFC has been limited due to following reasons [10]:

1. High Cost: Converter complexity and high semiconductor ratings make UPFC an expensive solution. Moreover, the series and shunt converters voltage isolation need three-phase high-voltage transformers. Lastly, it involves a big zone for implementation and calls for expert work for the problem fixing in UPFC parts, which added more cost.

2. Low Reliability: A single component failure can prove to be fatal in the overall performance of the module. If any failure occurs at the shunt converter, the consequences will be as device disconnection from the network. For a series device failure, it doesn't affect the device only, but as well disengages the transmission lines from the power grid as it is directly inserted into transmission lines.

All the disadvantages mentioned for the UPFC can be discarded by using DPFC. The limitations listed above for UPFC can be attributed to the designing construction of UPFC. The reliability of the device can be increased and the cost can be decreased if the same control capability is served by replacing a lumped controller into smaller controllers and distributing them over the grid. By using DPFC, low cost and high performance can be realized.

1.4 Objective of Thesis

This thesis mainly focuses on demonstrating the efficiency of DPFC device by evaluating its performance to control power flows for power system through comparison between the theoretical and practical results and then verify its efficiency in improving electrical power quality through studying the dynamic effect of it to mitigate sag in voltage and swell in the current.

This study enhances the concept of minimizing the limitations of UPFC. Distributed Power Flow Controller is established by removing the common DC link present between the shunt and series converters in UPFC and distributing the series converters over the transmission line. The DPFC is a modern and developing device, it is similar to UPFC in structure. There are two main differences between UPFC and DPFC the first one, is that in UPFC there is a common DC-link between the shunt and series converters but in DPFC this DC link is eliminated and in place of this DC link the transmission line is used to exchange power between series and shunt converters and the second difference is that UPFC has one three-phase series converter but the series converters in DPFC are single-phase and distributed through the line as a separated series converter.

The steady state, step response and dynamic performance analysis are obtained to verify the principle of DPFC using MATLAB/SIMULINK software.

1.5 Organization of Thesis

The work carried out in this thesis is divided into six chapters and its organization is given as below:

Chapter 2: In this chapter, the principles of power flow control and power quality improvement by using various FACTS controllers are discussed. Also, the configuration and connecting ways for facts devices with power system are explained.

Chapter 3: In this chapter, the principle of DPFC is explained. Also, the concept of deriving DPFC from UPFC and the Distributed FACTS concept is employed to the series converters. Also, the steady-state performance of DPFC is studied in this chapter. The mathematical model of the DPFC has studied in this chapter also and based on these mathematical calculations the performance is evaluated.

Chapter 4: In this chapter, the modeling, design and basic control for DPFC are realized. By using Park's DQ transformation the AC components of DPFC are transformed into DC components and components of DPFC are controlled by the traditional PI controller. This control is answerable for controlling and fixing DC voltage of the DPFC converters and generating the AC voltage by series converters.

Chapter 5: In this chapter, the performance evaluation of DPFC is demonstrated in SIMULINK/MATLAB through simulation of DPFC at different operating conditions. Firstly, the model of DPFC is simulated under steady-state condition. Simple two bus system is applied with two voltage source block interconnected through an RLC series branch blocks representing transmission line. The device and its controls are also developed in SIMULINK. Secondly, the power quality improvement by using DPFC controller is developed and verified dynamically by connecting this device to RLC load through two transmission lines connected in parallel.

Chapter 6: This chapter gives the conclusion of the work carried out and addresses the issues that can be considered for future work.

CHAPTER TWO

POWER FLOW CONTROLLING DEVICES

2.1 Introduction

The demand for the electrical energy rises continuously, this rising in demand day by day leading to more stress of the transmission lines, also electric power utility industry is suffering constantly changes due to privatization and competition in electricity markets in many leading countries. All this makes it necessary for electric power utility industry to competitive structures, which means that the secure and economic operation of power systems is opposite a new challenge along with the more competitive market environment [11].

The pressure related with the reasonable cost effect and environmental limitations has obligatory the power utilities to try to meet the growing demand for the future request for energy completely by utilizing the standing resources of transmission facilities without any construction for newlines.

In the last two decades of the nineteenth century, electronic devices developed rapidly, with this fast development of power electronics devices and the possibility of exchange the electrical energy by export/import this energy and moving transactions between the utilities, it has become necessary to think in new ways to organize the work of electrical networks. The electric power research institute EPRI presented a novel method to find right and appropriate solutions for problems of the power system, the offered concept is identified as flexible AC transmission systems FACTS devices were originally launched to solve the emerging problems [12].

The increasing of power electronic components capabilities made expansion of FACTS -devices faster. FACTS devices became available for high and even highest voltage levels with high power levels. The general initial points are network parts which have an effect on the impedance or the reactive power for any element in the electric power system network. For the FACTS concept, there are two basic terms used under this concept known as 'DYNAMIC' and 'STATIC' these two terms used as a classification for facts devices.

These two terms need some explanation. When the power electronics of FACTS devices provide fast and reliable control ability, the expression 'DYNAMIC' is used to express the quality of control ability. This term is the important and it’s the main difference from the conventional devices that used in power quality improvement field. Because there are no moving parts in these devices like mechanical switches that used to perform the dynamic controllability, the second term 'static' is used as a description of these devices. So, at the same time most of the FACTS -devices can be classified as static and dynamic.

The FACTS controllers give real possibility and great chances to regulate the alternating current parameters in the transmission system and power flow control by increasing or reducing the flow in specific transmission lines.

The FACTS technology extension is based on the controlling ability of the power flow route and the capability of joining networks that are cannot interconnect for technical reasons and it gives the possibility of energy trading among distant agents [13].

2.2 Power Flow Theory

At any power system, the transmission line can be characterized by four parameters: resistance, capacitance, inductance and conductance. Where conductance is a measure for the current that leaks at the insulators of the overhead transmission lines. However, in the short and medium length transmission lines that have a length (less than 240 km), the magnitude of capacitance and conductance are very small, so that it can be ignored with little loss of accurateness [14]. According to that a transmission line can be represented as Figure **2**.1, where Vs and Vr are line-to-ground phasor voltages at sending and receiving end, I is the phasor current through the line, R is the value of series resistance and L are the value of the inductance of the line.

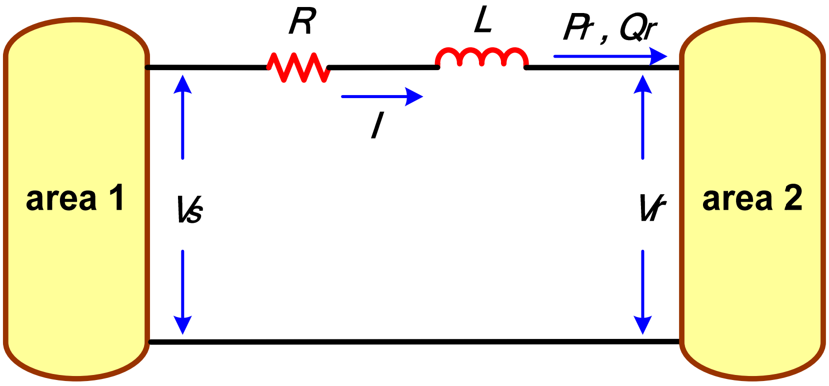


Figure 2.1: Simple Diagram of one-line representation of a transmission line.

From Figure 2.1, the power flow Sr that flows at the transmission line at the receiving end is given by[15]:

$$S_r = P_r + jQ_r = V_r \cdot I_1{}^* = V_r \cdot \left(\frac{V_r - V_s}{R + jwL}\right)^* \tag{2.1}$$

Where the symbol (∗) means the conjugation of a complex number, and ω is the angular frequency of the power system[14]. The transmission line impedance can be substituted by Z and it is equal to R + jωL. In a typical high-voltage or medium voltage transmission line, the reactance is usually much larger than the resistance [16]. Therefore, the resistance can be ignored during the power flow calculation with little loss of accurateness, and the active and reactive power flow through a lossless line can be simplified to the following [15]:

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

$$(2.2)$$

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

Where X = ωL is the inductive impedance of the line. Equation (2.2) shows that three system parameters can be utilized to vary the power flow; transmission angle θ, line impedance X and bus voltage magnitudes |Vr| and |Vs|. Because power systems are operated in a unified voltage mode (voltages are close to 1 per unit)[14]. 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:

$$P_r = \frac{|V|^2}{X}\sin\theta \qquad \text{and} \quad Q_r = \frac{|V|^2}{X}(\cos\theta - 1) \tag{2.3}$$

As shown, the active and reactive power flows are coupled. By varying one parameter, both active and reactive power flow will change accordingly.

2.3 Definition of Facts

FACTS is the shortening of Flexible Ac Transmission Systems. According to IEEE, is defined as follows, “alternating current transmission systems incorporating power electronics based and other static controllers to enhance controllability and power transfer capability” [12].[17].

2.4 Possible Benefits of FACTS Technology

FACTS-devices offer an improved harmony to varying operation circumstances and increase the usage of current installations by giving the possibility to the transmission and distribution systems to get one or more of the following benefits[18]:

1. Power quality improvement. Thus, letting the lines to carry more active power, lower system losses, better stability of the network.
2. The ability of controlling Power flow.
3. Reactive power enhancement.
4. Stability enhancement, through dynamic transient and steady state stability enhancement, power oscillation damping and control voltage stability.
5. Increasing of transmission capability.
6. Voltage control.

a. The interconnection possibility between the renewable energy source and distributed generation to the power grid.
b. Offer safe tie-line joining to neighboring utilities and areas which decrease overall generation reserve requirements on both sides.

2.5 Technological Features

FACTS devices can be classified according to technological structures into two generations:

2.5.1 First Generation

The principle work of the first-generation of FACTS devices rely on impedance or tap changer transformers controlled by thyristors to control power system flow. The thyristors with ignition controlled by a gate SCR is used in this generation. This group has produced in many types like Thyristor-Controlled Series Compensation, Static Var Compensation, and Thyristor Controlled Phase Shifting.

2.5.2 Second Generation

in this generation, the GTO semiconductors with ignition and extinction controlled by Gate Turn-Of Thyristor are used, the second-generation depend on using converters, using electronic tension sources such as (3-phase inverters, synchronous voltage sources, auto-switched voltage sources, voltage source controller) [16]. This generation types are Insulated Gate Bipolar Transistor, Integrated Gate Commutated Thyristor, Metal-oxide semiconductor Controlled Thyristor, etc. It has produced in UPFC, UPQC, DPFC, STATCOM, SSSC and the IPFC.

2.6 Configurations of Facts-Devices

FACTS devices can be coupled with an electric transmission line in three main ways [17]:

1- Series Connection with the power system (series compensation) like SSSC and TCSC.
2- Shunt Connection with the power system (shunt compensation) like SVC and STATCOM.
3- Both in Shunt and Series connection like TCPST and UPFC.

2.6.1 Model of Shunt devices controllers/Static Synchronous Compensator STATCOM

Shunt fact devices inject current at a common point between the device and the system. They might be convertible impedance, convertible source, or a combination of convertible impedance and convertible source. There are diverse shunt-connected FACTS devices, the most famous among them in terms of the applications is the static

VAR compensator SVC or the type which known as STATCOM that come with Voltage Source Converter. Shunt controller is to a certain extent similar to a current source, which draws current from the line or injects it into the line. Therefore, at the point of connection between shunt device and grid a leading or lagging reactive current is injected, Shunt controller, is an effective way to control and damp oscillations of voltage. These shunt devices can work as reactive power enhancement devices [13]. The disadvantage of using SVC, besides their slower response, is the fact that their ability to provide VAR support is voltage dependent. Shunt VAR is normally required when the system voltage is depressed and during these periods the ability of SVC to provide VAR support is also seen to decrease [13].

STATCOM can be operated in inductive or capacitive regions by making a change in the output voltage magnitude with respect to bus voltage. It is the static sample of the rotating synchronous condenser but because there are no moving parts inside it, it can inject or draw reactive power quickly. In principle, it achieves the same voltage regulation purpose as the SVC but in a stronger way because of the difference from the SVC, its work is not affected by the attendance of low voltages. Figure 2.2 shows the structure of static synchronous Compensator [19]. STATCOM is seen to be more robust in providing reactive support to the network as their level of injection is independent of the variations in system voltage.

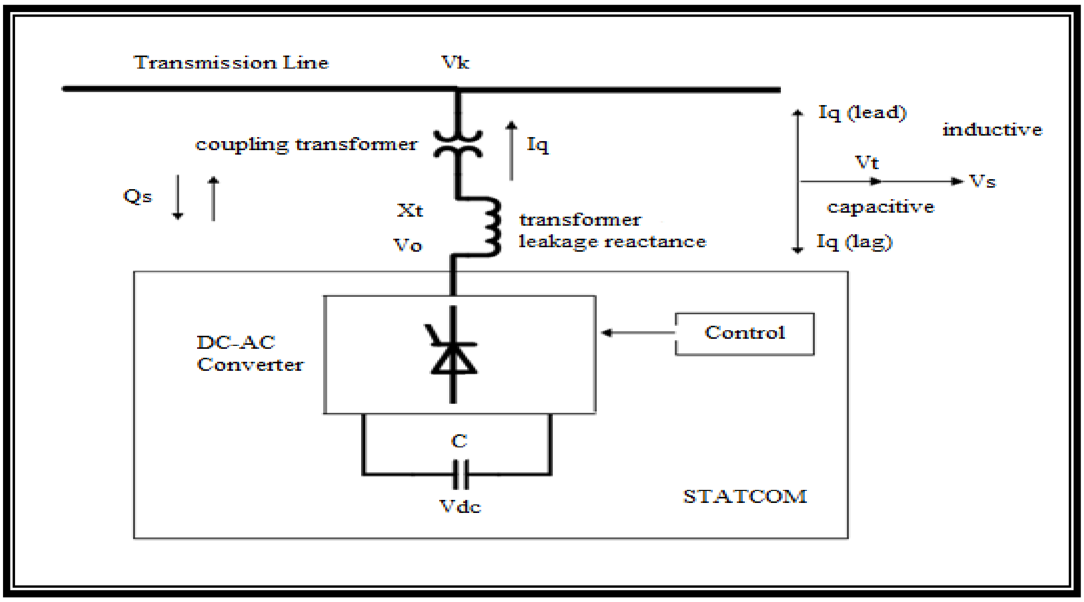


Figure 2.2: The structure of static synchronous Compensator.

Today while the application of the VSC became more practical in the distributed energy area especially for the combination old sources with a new one and with the development of distributed energy storages (large storage capacitor, battery, superconducting magnet) the power quality improvement and balanced network operation can be achieved by the STATCOM [20].

2.6.2 Model of Series Devices Controllers SSSC

Series FACTS devices are the devices that depend on power electronics as working principle and it has the ability to inject a voltage in series to the electrical transmission line.

A Static Synchronous Series Compensator SSSC is one of the series devices that coupled in series to the transmission power system. It can be shown as one of an advanced facts device which takes place on the set of series-connected FACTS devices.

The working principle of this device is similar to the STATCOM. It coupled to the transmission line by coupling transformer and uses a VSC interfaced, which generates a controllable alternating voltage at the fundamental frequency. A large energy source is required to provide and maintaining the DC voltage over a condenser (DC capacitor) and to restore the losses of the VSC by injecting voltage which controlled in phase and magnitude, but if the aim of using SSSC is only reactive power balancing, the energy source might be pretty small. Even though the main purpose of using an SSSC is power flow controlling at power system steady-state operation, it also has the ability to enhance power system transient stability. One of the SSSC versions that practically applied in power systems at distribution stage is the Dynamic Voltage Regulator DVR that essentially contains a three-phase converter coupled with a transformer. The main aims of using DVR is to keep the voltage at a constant level [21]. Figure 2.3 shows the SSSC configuration [22].

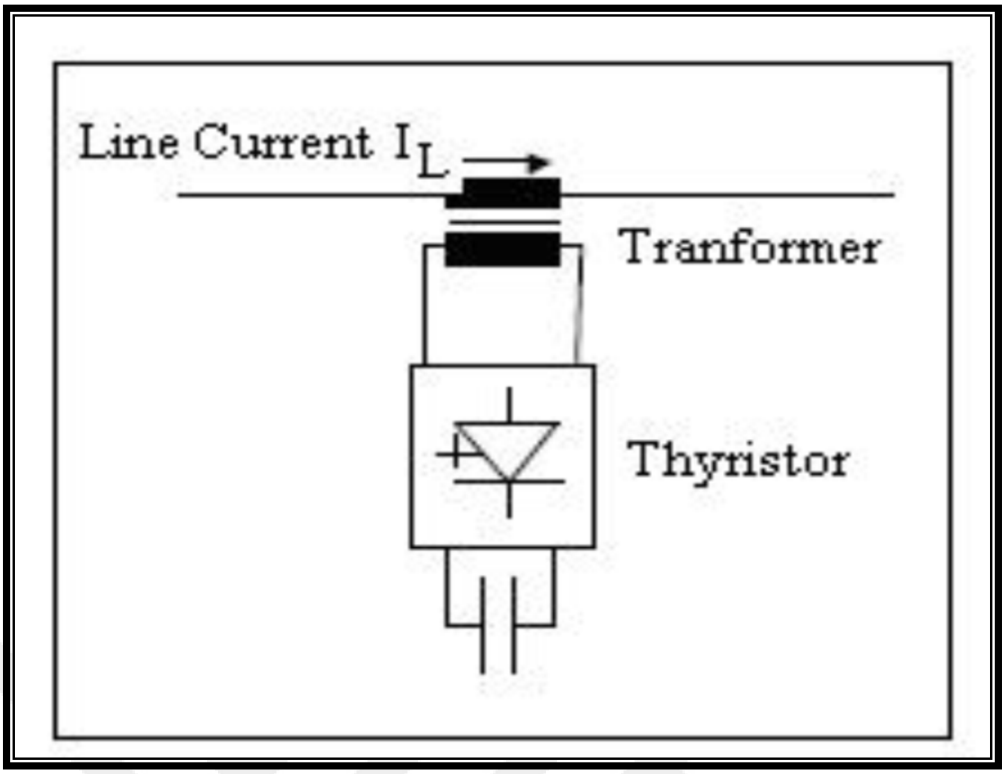


Figure 2.3: Static synchronous series compensator.

2.6.3 Model of Combined Shunt and Series Devices/ Unified Power Flow Controller UPFC

The UPFC was suggested by Gyugyi [13]. The UPFC has the ability to control all three parameters of the transmission line at the same time to control line power flow. These three parameters are a line voltage, impedance and phase angle. This modern fact device includes the structures of two ancient facts devices together: the STATCOM and the SSSC. The idea behind the UPFC designing is that, since these two devices are connected in series with the transmission line through a series transformer in SSSC and in shunt with the transmission line through a shunt transformer in STATCOM, by connecting these two devices to each other by a common DC link including a storage capacitor can be obtained a new design which is UPFC, by using UPFC concept, different control range possibilities are available in comparison with STATCOM or SSSC. Figure 2.4 shows Basic circuit arrangement of UPFC [23].

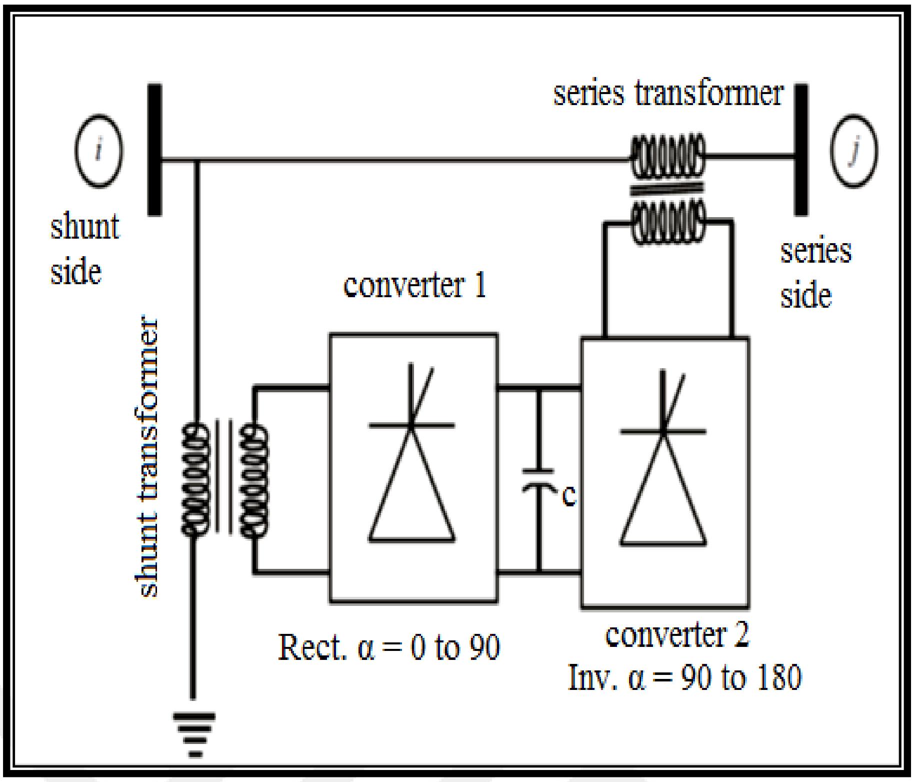


Figure 2.4: Basic circuit arrangement of UPFC.

Between the existing FACTS devices, UPFC is recognized as the most multipurpose, sophisticated, multifunction and powerful device using to control power flow, at the other side, the optimal control problem for UPFC is most complex. Probably it's the most expensive one of the other FACTS devices. Uniting the structures of the static compensator STATCOM and the static series compensation SSSC, gives an another way to alleviate power system fluctuations [13]. It is of attention to know that impact of UPFC in mitigation the troubles in voltages, currents and maintaining power flows under fault situations, not only in the transmission line where it is connected but likewise in the nearby parallel transmission line. Further, how the importance of UPFC contribution to a quicker recapture of the system as before-fault situations.

During steady-state circumstances, the demand of real power that series converter need is provided by the shunt converter. Under transient circumstances, the demand of real power for the series converter is provided by the DC link capacitor.

CHAPTER THREE

DISTRIBUTED POWER FLOW CONTROLLER DPFC

3.1 Distributed Power Flow Controller DPFC

The distributed power flow controller can be viewed as a modern type of (shunt – series) facts device controller that has the ability to improve the power quality of the electrical power system. The DPFC operating technique is same as the UPFC. It gives results similar to UPFC when it used to compensate power system disturbances such as the voltage sag and the current swell which considered a task problems of power quality problems but in high reliability and low cost. As compared to UPFC the common DC link that connects shunt and series converter together is eliminated and instead of this DC link the transmission line is used as connection between the shunt and the series converters and three separate single-phase converters are used in place of a three-phase series converter as shown in figure 3.1[24].

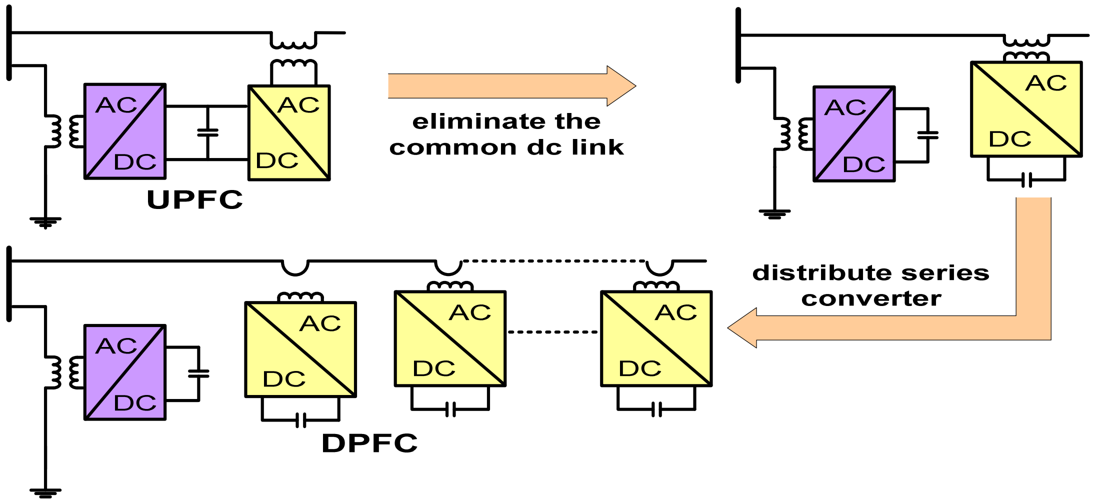


Figure 3.1: Flowchart of convert UPFC to DPFC.

3.2 Working Principle of DPFC

DPFC is derived from UPFC. When we compare DPFC with UPFC, the most important benefit presented by DPFC is the elimination of the huge DC-link between series converters and shunt converter and instead of that DC-link, the transmission line and 3rd-harmonic current are used as ways to exchange the power between shunt and series converter. The shunt converter injects 3rd harmonic current to the transmission line and through the transmission line this current arrive to the series converters. This elimination making DPFC much less expensive from UPFC. Theoretically, the other harmonics can work for the same purpose as the third harmonic to exchange active power in the DPFC like, sixth harmonic, and ninth harmonic frequency. All of these harmonics are zero sequence frequencies. The 3rd harmonic is the preferred frequency to exchange active power in DPFC because of the transmission line impedance is inductive and related to the magnitude of frequency, so when a high degree of transmission frequencies are used this will leads to high impedance. For this cause, the third harmonic frequency is chosen because the third harmonic is the lowest zero sequences harmonic frequency[10]. In the next sections; the DPFC basic principle is described.

The DPFC comprises of one shunt and several separated converters coupled in series with the power transmission line. The arrangement of the DPFC is given in Figure 3.2.

In addition to the main components, there are essential equipment that must be available in order for the DPFC function properly, the DPFC involves a high-pass filter connected between the transformer and ground at the next side of the transmission line, and two transformers the first one is a Δ-Y connection and the second transformer connection is Y-Δ [25].

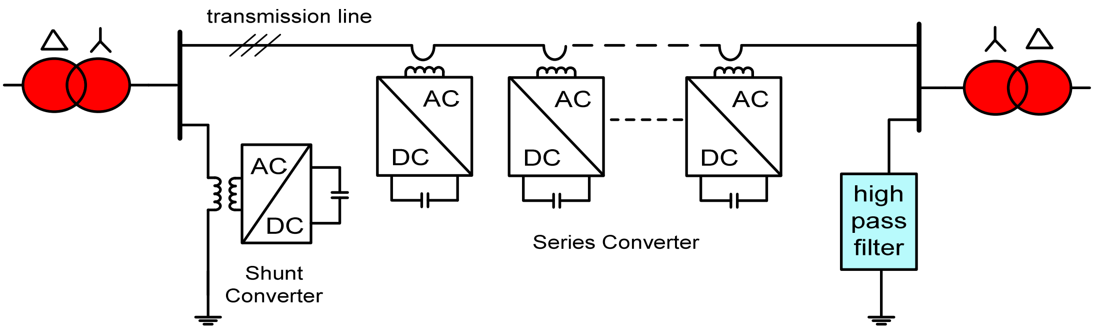


Figure 3.2: Dpfc structure.

3.2.1 Power Exchange and DC Link Elimination

In the DPFC, the connection tool between the series converters terminals and DC terminal of shunt converter is transmission line that can use to exchange active power and provide connection path in place of common DC link [25]. To exchange power in DPFC, the concept of non-sinusoidal component theory of power is used.

According to Fourier series [2]. A non-sinusoidal element of voltage or current can be presented as the sum of sinusoidal components at different frequencies. The active power can be obtained from the multiplication of the voltage and current components, according to that the active power equation is given as:

$$P=\sum_{i=0}^{\infty} V_i I_i \cos \emptyset_i \tag{3.1}$$

Where,V_i is the voltage at i^{th} harmonic, I_i is the currentat i^{th} harmonic, and $\cos \emptyset_i$ Is the angle between the voltage and current at the same frequency. Equation 3.1 defines that the active powers at different frequencies are separated from each other and the voltage or current in one frequency has no impact on the active power at other frequencies [26]**.** So, according to this principle the shunt converter in DPFC has ability to absorb active power from the network at the fundamental frequency and inject the current back into the network at a harmonic frequency. Also, the series converter in DPFC can generate the voltage at the harmonic frequency this achieved by absorbing the active power from harmonic components [27].

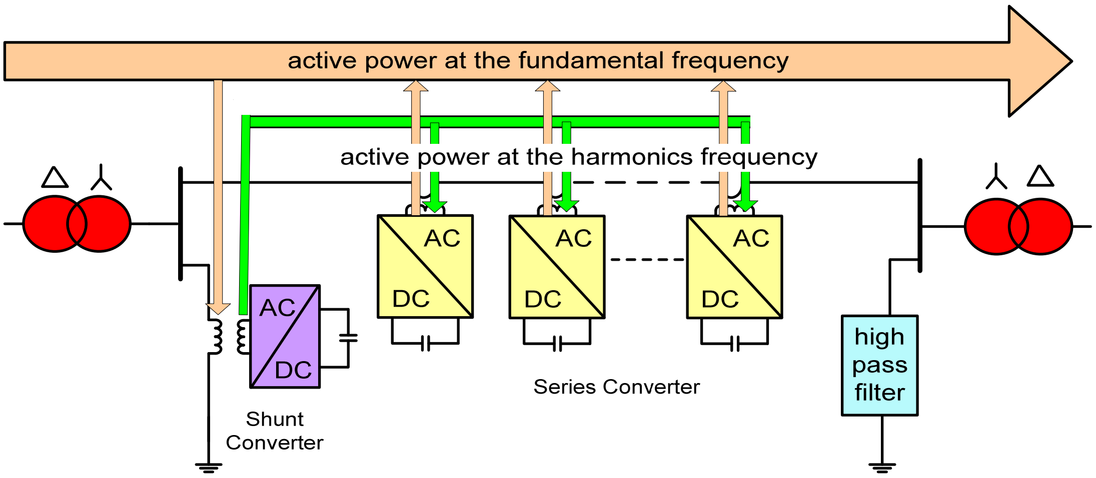


Figure 3.3: Active power exchange.

On the assumption that DPFC is located in a transmission line with two-buses, as explain in Figure 3.3 whereas the sending end generator produces the active power, the shunt converter of DPFC has the ability to draw power in fundamental frequency.

In general, at any three-phase power system, the third harmonic frequency in each phase is identical and it can be known as “zero sequence”. The Y-Δ transformer naturally can be blocked zero-sequence harmonic and prevent it from passing to the network as shown in figure 3.4.

Therefore, the components of the third harmonic are strangled in the Y-Δ transformer. The exits terminals of the shunt converter insert the third harmonic current into the neutral point of Δ-Y transformer. Subsequently, this third harmonic current produced by shunt converter flows over the power transmission line. This third harmonic current controls series capacitors DC voltage of the series converter.

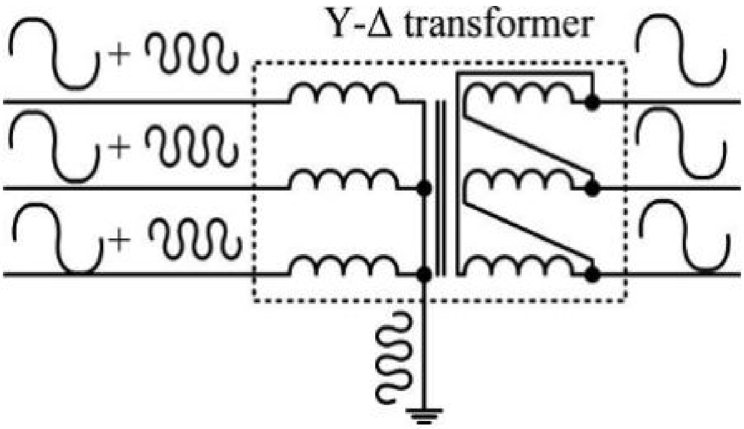


Figure 3.4: Using A Y-Δ transformer to block zero-sequence harmonic [25].

One of the basics of the working principle of DPFC is that third-harmonic is used as a means to exchange the active power so that the existence of a high-pass filter is necessary to produce a closed loop path for this harmonic current. The high-pass filter can be substituted with a cable. This cable connects star winding of the transformer to the ground [28].

This cable will be as a path to the harmonic current to the ground as shown in figure 3.5 So that, there is no necessity to use the high-pass filter in the system receiving-end.

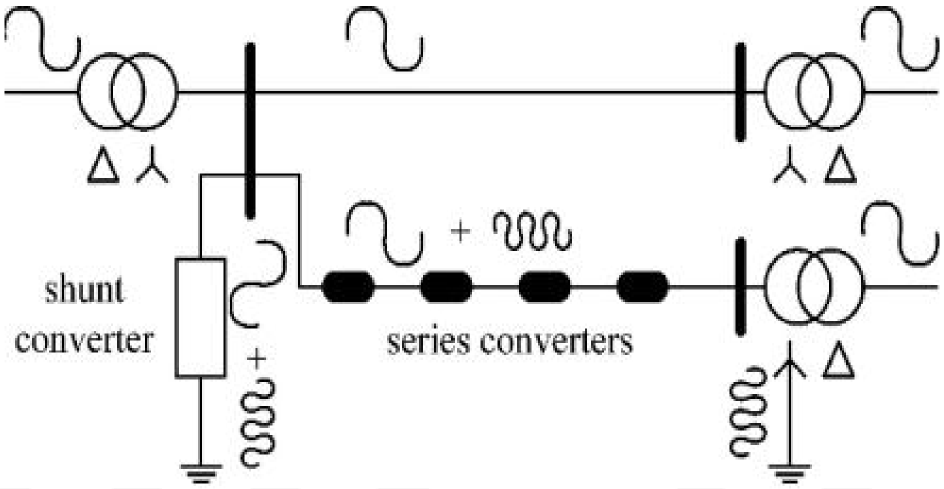


Figure 3.5: The harmonic current path between transformer and ground.

3.2.2 The DPFC Advantages

Compared to other FACTS devices, DPFC has economic and practical advantages that can be summed up in the following points [2]:

1) High Control Capability: The DPFC is derived from UPFC, and has same control capability as UPFC it can control all basic power system network parameters such as line impedance, transmission angle degree and bus voltage scale.

2) More Reliability: The separation of series converters to many groups that distributed through a transmission line rises the DPFC reliability through converters working. This means that if one of series converters be faced with any problem that causes fails, the others can continue to work.

3) Lower Cost: The cost of using DPFC is lower than UPFC for two main causes:

The first: is no needing to DC link between converters like UPFC.

The second: the cost of using many single-phase converters in series with transmission line is lower than using one three-phase converter. That's because the connection of series converters to the transmission line does not require any high voltage isolation. Instead of the high voltage isolation, a single-turn transformer can be used to hang the series converters through the transmission line.

3.3 DPFC Explanation and Equivalent Circuit

From the theoretical viewpoint, each converter in DPFC can be substituted by an equivalent impedance connected in series with a controllable voltage source [3].The converter can be compensate with double controllable voltage sources coupled in series. The possibility of this representation is because each converter can generate a voltage at two different frequencies, one voltage is produced at the fundamental frequency and the other voltage is produced at the 3rd harmonic frequency. If we consider the converter is working without loses, the theoretical description of DPFC is shown in Figure 3.6.

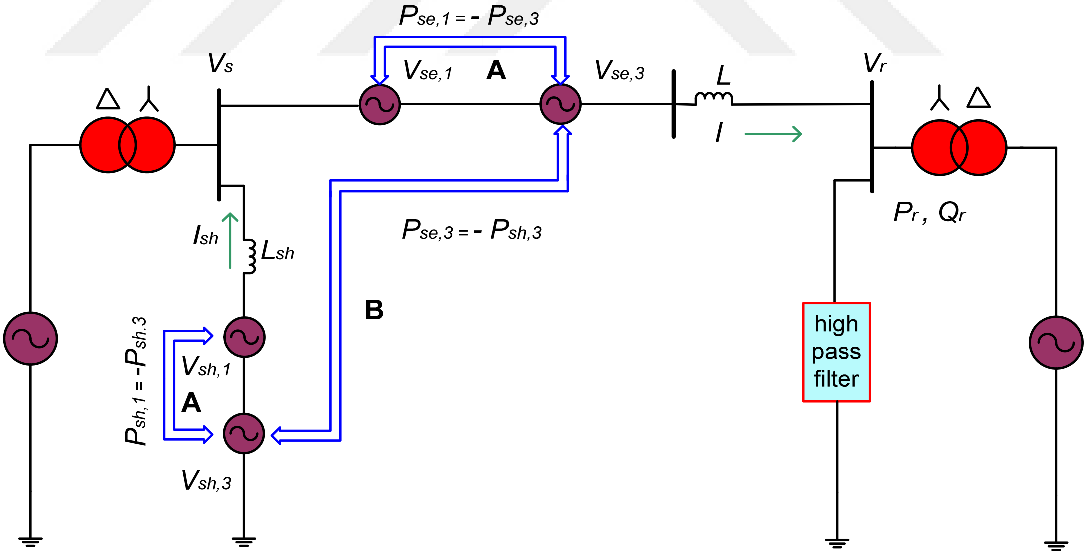


Figure 3.6: DPFC simplified representation [3].

Where Vse,1 equivalent to the summation of series converters voltage at the fundamental frequency, and Vse,3 is equivalent to the summation of the 3rd harmonic voltages, the shunt converter is controlled to generate a voltage at the 3rd harmonic frequency. As a product, this 3rd harmonic current will inject into the transformer neutral point at star side and flow over the transmission line to supply the active power to series converters. The series converters absorb the active power from third-harmonic frequency to equilibrium and regulate their DC voltages. Based on the superposition theorem, the two circuits for two frequencies can separate from each other, the circuit can be divided into two circuits at two frequencies[2]. And the active power will be as a link between two circuits to provide stability for each converter, see figure 3.7.

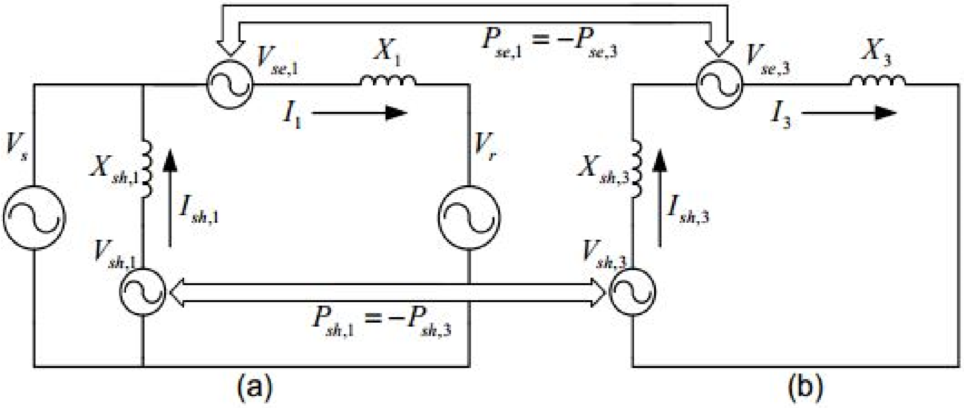


Figure 3.7: DPFC equivalent circuits in(a) fundamental and (b) 3rd harmonic frequency.

3.4 Steady – State Analysis of DPFC

To study the DPFC steady- state performance, the DPFC can be expressed by replacing each converter in DPFC by an impedance connected in series with a controllable voltage source to produce the voltages at two different frequencies [26]. On this assumption, the DPFC is located through two-bus system, the sending end voltage is Vs and the receiving end voltage is Vr as given in Figure 3.8.

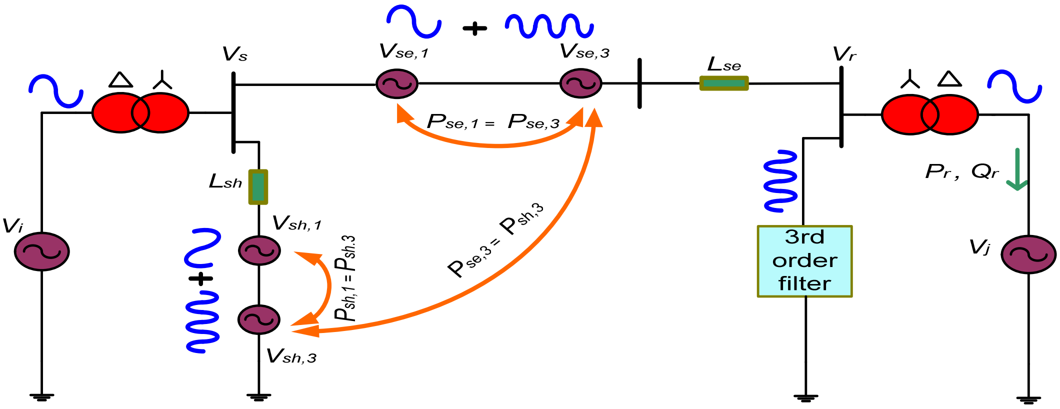


Figure 3.8: Basic illustration of DPFC in two bus system [26].

For steady-state analysis, the transmission line is analytically represented by a line current I with an inductance L. Where Vse1 represent the voltage injected by series converters at the fundamental frequency and Vse3 is the voltage injected by series converters at the third harmonic frequency. The shunt converter is linked to the sending end bus by an inductor L,sh and generates the voltage Vsh1 and Vsh3. Pr and Qr are the active and reactive power flows at the receiving end, respectively.

The capability of the DPFC to control power flow can be shown by the active power Pr and reactive power Qr at the receiving end. The reference for power flow capability illustration is figure 3.7. According to this figure, the flow of active and reactive power can be stated as follows [29].

$$P_{(r)}+JQ_{(r)}=V_{(r)}I^{*}_{(1)} = V_{(r)}\left(\frac{V_{(s)}-V_{(r)}-V_{(se.1)}}{jX1}\right)^{*} \tag{3.2}$$

Where X1 = ωL1 is the impedance of the transmission line at the fundamental frequency. The power flow Pr, Qr contains two parts: Pr0, Qr0 which refer to the power flow without DPFC connection and Pr,c,Qr,c that is the part that is mixed by the DPFC compensation. The power flow lacking to DPFC attendances Pr0,Qr0 is given by[3]:

$$P_{r(0)} + jQ_{(r0)} = V_{(r)}\left(\frac{V_{(s)}-V_{(r)}}{jX_1}\right)^{*} \tag{3.3}$$

DPFC power flow control range can be stated as follows [26]:

$$P_{r.c} + jQ_{r.c} = V_r\left(\frac{V^{*}_{se1}}{jX1}\right) \tag{3.4}$$

Where Pr,c is the active power flow control range of DPFC, and Qr,c is reactive power flow control range of DPFC.

As the line impedance and the voltage at the receiving end are fixed, the power flow control range of the DPFC is related to the series converter maximum voltage, the way of controlling the active and reactive power flow over the transmission line obtained from the phase angle of voltage V*se1 that can be rotated over 360◦,From Eqn. (3.2) and Eqn. (3.3), the control ability of the DPFC is given by [3], [2]:

$$(P_r - P_{r.0})^2 + (Q_r - Q_{r.0})^2 = \left(\frac{|V||V_{se.1}|}{X_1}\right)^2 \tag{3.5}$$

The magnitude of the injected voltage that injects by the series converter Vse1 at fundamental frequency can be obtained from the following equation [2]:

$$V_{Se1}= \left[\frac{(S_R - S_{R0})jx_1}{V}\right] \tag{3.6}$$

Where Sr0 is the apparent power in transmission network without DPFC connection and Sr is the apparent power in transmission network with DPFC compensation. For the possibility of a 360◦ rotatable voltage injection, series converter should feed with an active and reactive power at the fundamental frequency, although the required magnitude of active power to compensate disturbances is provided by the shunt converter at the third harmonic frequency and this active power that flows through the transmission line, given as [2]:

$$P_{Se1} = \frac{X_1}{|V_R|^2} |S_R||S_{R0}| \mathrm{Sin}(\Phi_{R0} - \Phi_R) \tag{3.7}$$

Where the symbol φr0 reffers to value of power angle at the receiving end of the uncompensated power system and it is equal to tan-1 Pr0/Qr0 and φr is the receiving end power angle with DPFC compensation [26].

3.5 DPFC Control Circuit

To regulate the work of several converters in DPFC, there are three kinds of controllers, central control, shunt control and series control.

3.5.1 Central Control

To adjust the work of series control and shunt control to regulate shunt and series converters of the DPFC, reference signals are produced by central control. It is dealing with keeping DPFC tasks near the power-system level to keep it within the required work limits, such as power-flow control, balancing of asymmetrical components and low-frequency power oscillation damping. The central control gives equivalent reference voltage signals for the series converters and reactive current signal for the shunt converter according to the system requirement. All the reference signals made by the central control are at the fundamental frequency. A simplified diagram for DPFC control is shown in figure 3.9 [4].

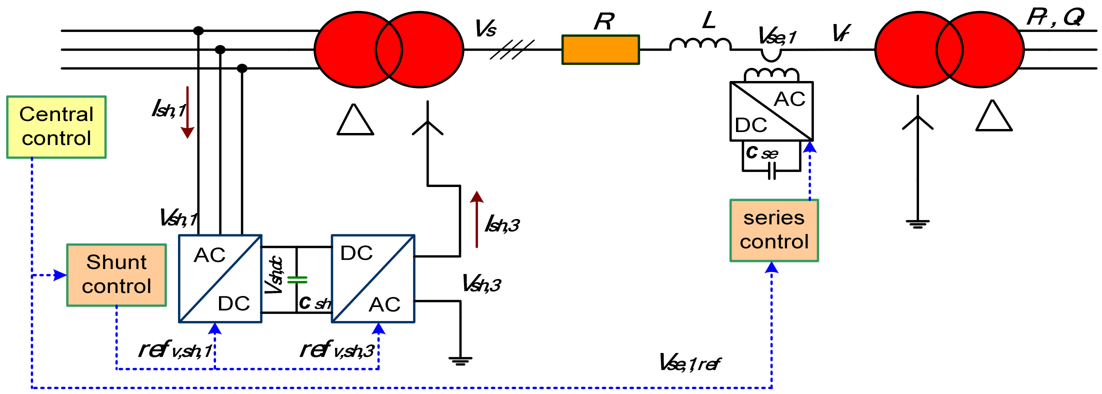


Figure 3.9: Simplified diagram for DPFC control.

3.5.2 Shunt Control

The shunt part of DPFC comprises two converters. The steady 3rd harmonic current injected into the network by the single- phase converter. Another converter is three-phase converter and its task is to keep the DC voltage at a fixed value. Each converter has its own control independently. A simplified block diagram of the shunt converter controller is given in figure 3.10.

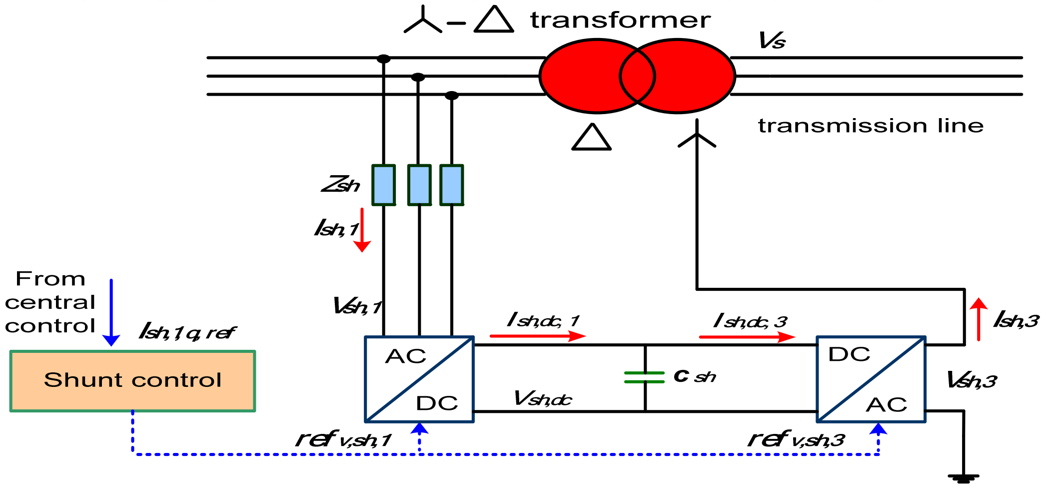


Figure 3.10: Simplified block diagram for DPFC shunt control.

3.5.3 Series Control

The series converters in DPFC separated from each other and they are single phase converters connecting in series with the transmission line, each converter is controlled locally by its own controller, and the control structures for each series converters are similar. For series converter control, isolated control loops are designed for the two frequencies components. To control DC voltage, the 3rd harmonic control loop is used. The DPFC series converter control simplified block diagram is shown in figure 3.11.

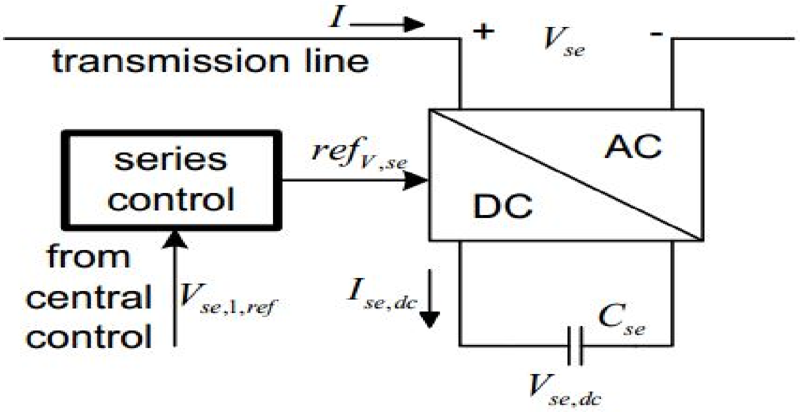


Figure 3.11: Simplified diagram for DPFC series control.

CHAPTER FOUR

DPFC MODELING AND CONTROL DESIGN

4.1 Introduction

This chapter presents modeling, design and basic control for DPFC. By using Park's dq transformation the AC components of DPFC are transformed into DC components and components of DPFC are controlled by the traditional PI controller. This control is answerable for controlling and fixing DC voltage of the DPFC converters and generating the AC voltage by series converters.

4.2 Modeling of DPFC

The DPFC principle of work depends on using transmission line as a link to connect the shunt and the series converters. The main parts of the DPFC are:

1. Shunt converter.
2. Series converters.
3. Power system transmission line.

The model of DPFC describes the performance of DPFC at the system level. The series converters at DPFC are single phase converters and these converters are designed as single-phase system. The network is designed as three single-phase networks with a 120-degree phase shift. There are two essential tools used for DPFC modeling design, the superposition theorem and Park's transformation.

Because of DPFC signal comprises two frequencies, at first superposition theorem is used to isolate the components of the signal and then Park's transformation is used for signal analysis at a single frequency. To implement the DPFC the following models must be implemented:

1. Network model which consists of (fundamental frequency and third harmonic frequency).
2. Series converter models.
3. Shunt converter models.

4.2.1 Network Modeling

The network circuits at the two frequencies are isolated by the superposition theorem, then the mathematical illustration of a network with a DPFC at two frequencies is presented.

4.2.1.1 Fundamental frequency network modeling

For network modeling, the transmission line is considered to be as symmetrical with lines transposed along their lengths and the converters of DPFC are assumed to be as controllable voltage sources. With these considerations, at the fundamental frequency, the network with the series converters of DPFC can be simplified as shown in Figure 4.1.

In the equivalent circuit, $V_{se,1}$ represent the magnitude of the voltage that injected by the series converters at the fundamental frequency, Z_1 is the line impedance, Vs and V_r are the sending and receiving ends voltages, respectively. $V_{se,1}$, V_s, V_r and the current I_1 are column vectors, which contain the information for the three phases. The network is designed as three single-phase networks with a 120-degree phase shift. The relationship between series voltage and the line current I_1 according to the equivalent circuit is given by:

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

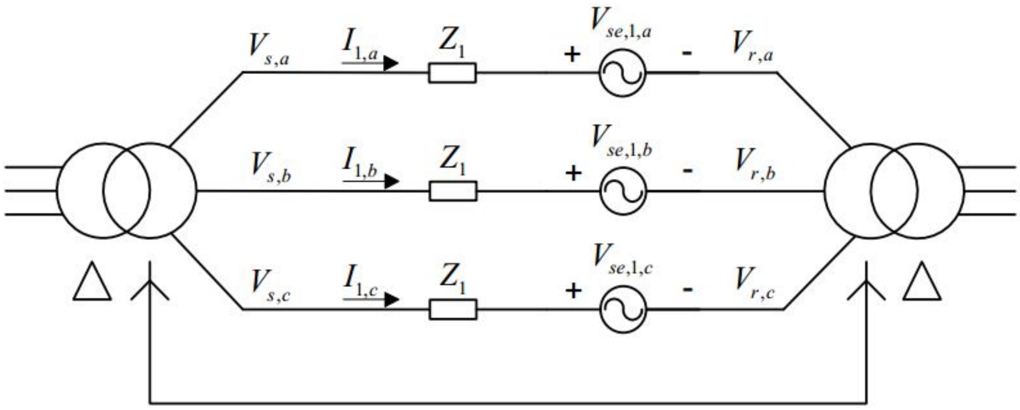


Figure 4.1: Equivalent circuit network of fundamental frequency.

The fundamental frequency model of DPFC illustrates how DPFC series converters have the ability to affect the current through the transmission line by changing the injected voltages.

4.2.1.2 Third harmonic frequency network modeling

The shunt converter in DPFC is modeled to inject 3^{rd} harmonic current to the network at the neutral point of the Y-Δ transformer. This current is evenly divided over the three phases of the transmission line and flow by a closed loop through the grounded neutral point of the other Δ-Y transformer.by compensation for converters with voltage source the 3^{rd} harmonic frequency equivalent circuit network can be clarified as shown in Figure 4.2.

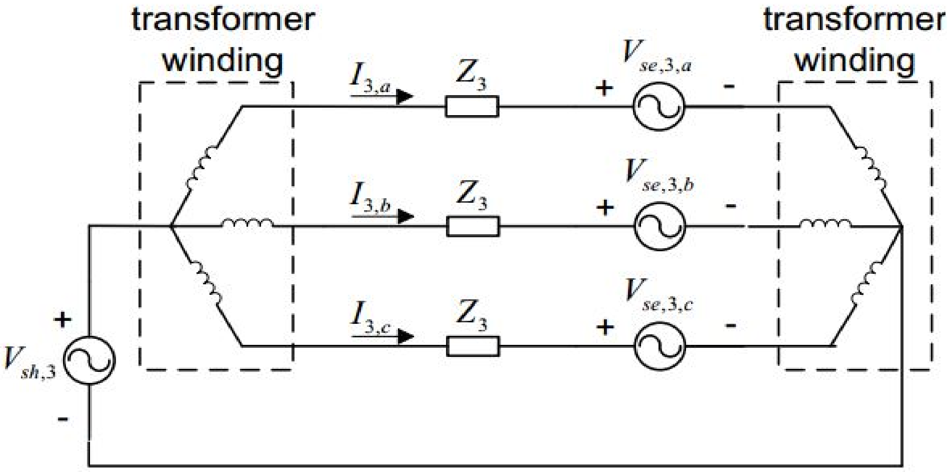


Figure 4.2: Equivalent circuit of 3^{rd} harmonic network.

The transmission line impedance and the two transformer windings with zero sequence reactance can be combined. The overall impedance at the third harmonic frequency can be denoted by Z_3. The impedance of neutral is considered to be zero. So, the relationship between the voltages and the currents at the 3rd harmonic frequency is given by:

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

The network model of third-harmonic represents the third-harmonic current in each phase, the input elements of this model are the voltages $V_{sh,3}$ and $V_{se,3}$ and the output of the model is the 3rd harmonic I_3 current of each phase.

4.2.2 Shunt Converter Modeling

The configuration of the shunt converter in DPFC contains a three-phase converter linked to a single-phase converter back-to-back. Like as a STATCOM, the main task of the three-phase converter is to absorb active power from the grid and it joined with the grid through the low-voltage side of Y-Δ transformer. The single-phase converter is located between the earth and the Y-Δ transformer's neutral point to insert 3rd harmonic current. The shunt converter simple diagram is clear in Figure 4.3.

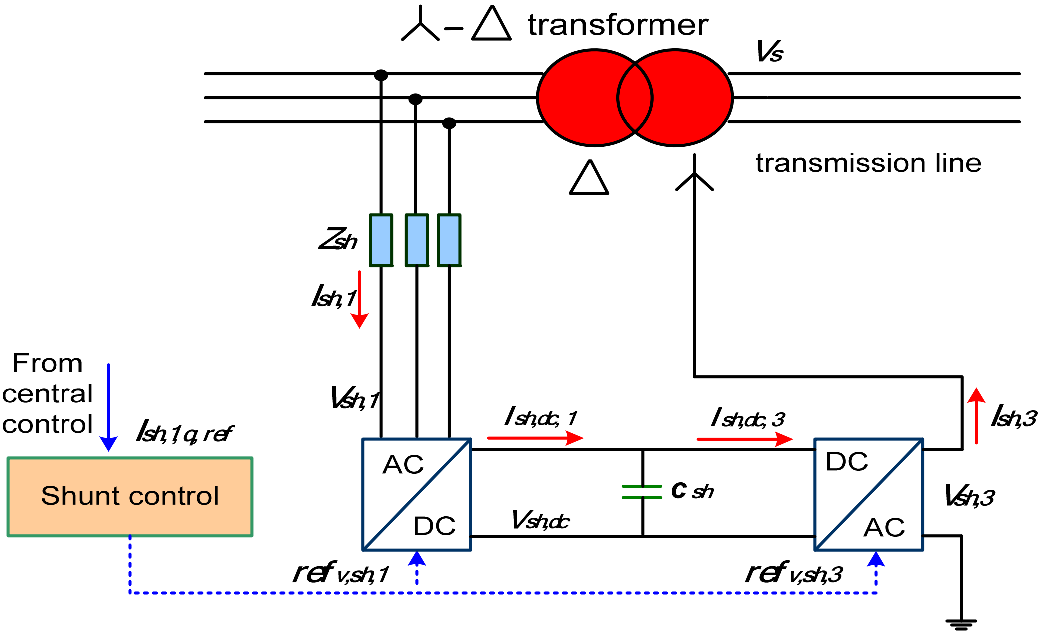


Figure 4.3: Shunt converter simple diagram.

The component of voltage Vsh,3 and current Ish,3 at the 3rd harmonic frequency are single-phase. The DPFC converter on the left side include only the components at the fundamental frequency which contain voltage $V_{sh,1}$ and the current $I_{sh,1}$.

4.2.2.1 AC side modeling

In shunt converter the AC voltage can be write in a similar way as to the series converter modeling, approximately written as:

$$V_{sh,1} = ref_{v,sh,1} . V_{sh,DC}$$

$$V_{sh,3} = ref_{v,sh,3} . V_{sh,DC} \tag{4.3}$$

where the amplitudes of $refV_{,sh,1}$ and $ref_{V,sh,3}$ in modulation are PU values and their range are between -1 to 1.

4.2.2.2 DC side modeling

The shunt converter capacitor DC voltage is given as:

$$C_{sh}\frac{dV_{sh,DC}}{dt} = I_{sh,DC,1} - I_{sh,DC,3} \tag{4.4}$$

By applying Park’s transformation to components of the fundamental frequency at the three-phase side the DC current is given as:

$$I_{sh,DC,1} = \frac{3}{2}\left(ref_{v,sh,1,d} I_{sh,1,d} + ref_{v,sh,1,q} I_{sh,1,q}\right) \tag{4.5}$$

The DC current $I_{sh,DC,1}$ can be constant with no ripple, If the three-phase components are symmetrical. The 3rd DC current can get it by substituting single-phase Park’s transformation by the 3rd harmonic components, it is given as:

$$I_{sh,DC,3} = \left(ref_{v,sh,3,d} \sin 3\theta + ref_{v,sh,3,q} \cos 3\theta\right) . \left(I_{sh,3,d} \sin 3\theta + I_{sh,3,q} \cos 3\theta\right) \tag{4.6}$$

The relations with zero-average values will not donate to the capacitor DC voltage while seeming as ripples of the DC voltage. By ignoring these relations, the shunt converter DC voltage is given by:

$$C_{sh}\frac{dV_{sh,DC}}{dt} = \frac{3}{2}\left(ref_{v,sh,1,d} I_{sh,1,d} + ref_{v,sh,1,q} I_{sh,1,q}\right) - \frac{1}{2}\left(ref_{v,sh,3,d} I_{sh,3,d} + ref_{v,sh,3,q} I_{sh,3,q}\right) \tag{4.7}$$

The final shape of shunt converter model, shaped by joining the AC and DC sides of the shunt converter model is shown in Figure 4.4.

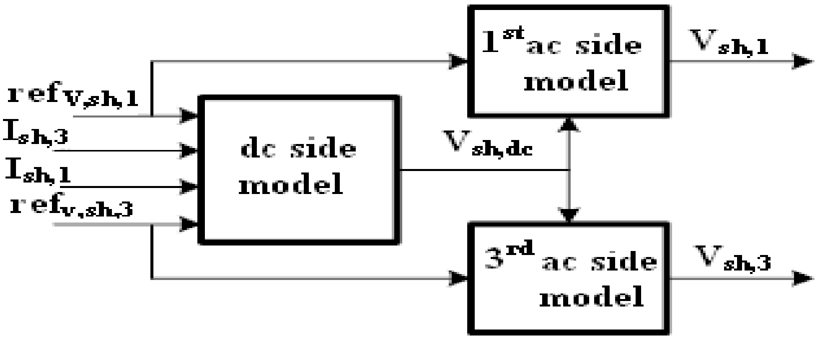


Figure 4.4: The shunt converter model block diagram.

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

4.2.3 Series Converter Modeling

The DPFC series converters are identical PWM control single-phase converters. The simple diagram for the series converter is shown in Figure 4.5. The converter losses are ignored for analysis simplifying.

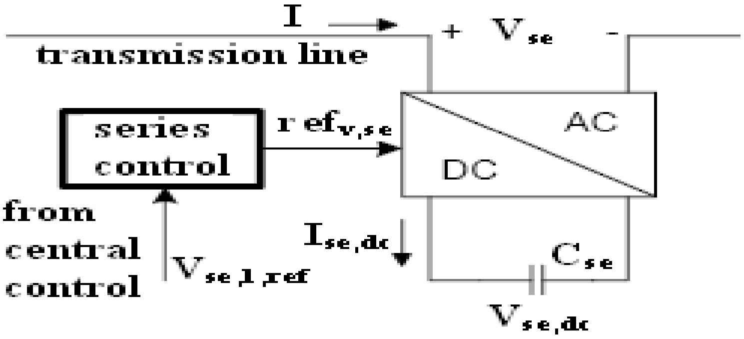


Figure 4.5: Series converter simple diagram.

V_{se} and $V_{,se,DC}$ are the series converter AC side and the DC side voltages, respectively. and ref$_{V,se}$ is the series control reference AC signal in PU, which is generated by the series controller. As shown in Figure 4.5 the AC voltages and currents comprise of two components at different frequencies, in another meaning the fundamental and the 3rd harmonic frequency components are denoted by subscripts V_{se} and their relationship is given as:

$$V_{se} = V_{se,1} + V_{se,3} \tag{4.8}$$

4.2.3.1 AC side modeling

The DPFC series converter is (PWM) control single-phase converter. The converter AC side voltage (V_{se}) can be rounded to the product of AC reference signal and the DC voltage multiplication process as given below:

$$V_{se} = ref_{v,se}.V_{se,DC} \tag{4.9}$$

The $ref_{V,se}$ is pu value with the range between -1 to 1. By applying the superposition theorem, can rewrite Eqn. (4.9) as:

$$\begin{bmatrix} V_{se,1} \\ V_{se,3} \end{bmatrix} = \begin{bmatrix} ref_{v,se,1} \\ ref_{v,se,3} \end{bmatrix}.V_{se,DC} \tag{4.10}$$

The series converter AC side model input signals are $ref_{V,se}$ and $V_{se,DC}$ and the output is the AC voltage V_{se}.

4.2.3.2 DC side modeling

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

$$C_{se}\frac{dV_{DC,se}}{dt} = I_{DC,se} \tag{4.11}$$

In the reference voltage and the AC current there are two frequency components. The series converter DC side voltage is written as:

$$C_{se}\frac{dV_{DC,se}}{dt} = \left(ref_{v,se,1} + ref_{v,se,3}\right).(I_1 + I_3) \tag{4.12}$$

and the DC current can be approximated to:

$$I_{DC,se} = ref_{v,se}.I = \left(ref_{v,se,1} + ref_{v,se,3}\right).(I_1 + I_3) \tag{4.13}$$

When the inverse single-phase Park's transformation is applying to Eqn. (4.12) we get:

$$C_{se}\frac{dV_{DC,se}}{dt} = \left(ref_{v,se,1,d}\sin\theta + ref_{v,se,1,q}\cos\theta + ref_{v,se,3,d}\sin 3\theta + ref_{v,se,3,q}\cos 3\theta\right).\left(I_{1,d}\,sin\,\theta + I_{1,q}\,cos\,\theta + I_{3,d}\,sin\,3\theta + I_{3,q}\,cos\,3\theta\right) \quad (4.14)$$

Where θ is the rotation reference frame angle for Park's transformation. The cross relations components of different frequency on the right side of Eqn.4.14, seem as zero-average ripples compose with the DC voltage. This ripple has no influence on the DC voltage magnitude, so during the modeling, the relations that cause the ripple are ignored. Thus, the DC voltage can be approximated to:

$$C_{se}\frac{dV_{DC,se}}{dt} = \frac{1}{2}\left(ref_{v,se,1,d}I_{1,d} + ref_{v,se,1,q}I_{1,q}\right) + \frac{1}{2}\left(ref_{v,se,3,d}I_{3,d} + ref_{v,se,3,q}I_{3,q}\right) \quad (4.15)$$

For DC side model the input signals are $ref_{V,se,1}$, $ref_{V,se,3}$, I_1 and I_3, and the output is the DC voltage $V_{se,DC}$. The overall design of the series converter model is as shown in Figure 5.6.

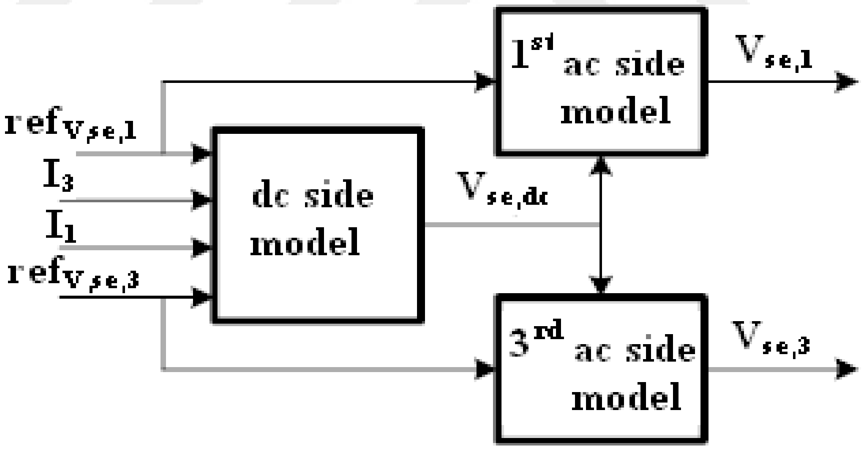


Figure 4.6: The series converter model block diagram.

4.3 DPFC Control

DPFC involves three types of controllers which are central controller, shunt controller and series controller. In this section, the shunt control and series control design is presented based on the mathematical model of DPFC.

4.3.1 Shunt Control

The shunt controller consists of two control circuits. The first one is fundamental frequency control circuit that be responsible of keeping DC voltage of the converter at a constant magnitude. The other one is 3rd harmonic frequency control circuit that is responsible of keeping shunt converter 3rd harmonic current injected to the grid regularly. The simple block diagram of shunt control model is shown in Figure 4.7.

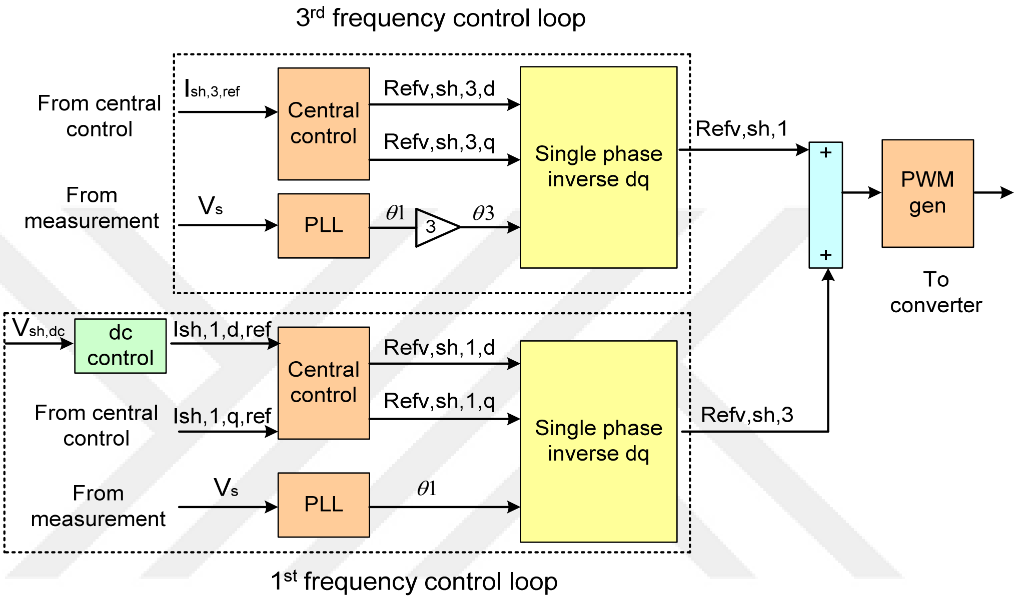


Figure 4.7: Shunt converter control block diagram.

The current control circuit is the more complex loop within the shunt converter's 3rd harmonic control and it is major loop. On the assumption that the DC voltage of the converter is fixed at a constant magnitude, the shunt and series converters can be characterized by voltage sources. From Figure 4.2, the 3rd harmonic circuit can be more shortened into two voltage sources coupled in series to a resistor and an inductor, as shown in Figure 4.8.

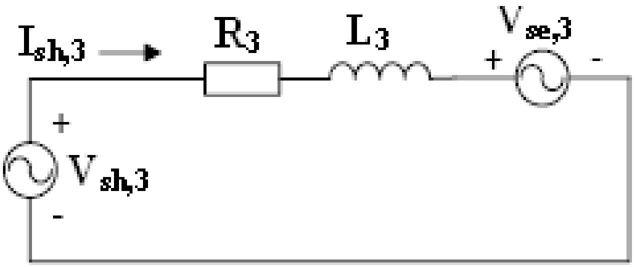


Figure 4.8: 3rd Harmonic simplified circuit.

At the 3rd harmonic frequency R_3 and L_3 are the network equivalent resistance and inductance. In the circuit the relation between voltage and current is:

$$V_{sh,3} = L_3 \frac{dI_{sh,3}}{dt} + R_3 I_{sh,3} + V_{se,3} \tag{4.16}$$

By using Park's transformation and applying it to Eqn.(4.16), in the dq-frame the relationship between the voltage and the current is given as:

$$V_{sh,3,d} = R_3 I_{sh,3,d} + L_3 \frac{dI_{sh,3,d}}{dt} - \omega_3 L_3 I_{sh,3,d} + V_{se,3,d} \tag{4.17}$$

$$V_{sh,3,q} = R_3 I_{sh,3,q} + L_3 \frac{dI_{sh,3,q}}{dt} + \omega_3 L_3 I_{sh,3,q} + V_{se,3,q} \tag{4.18}$$

4.3.2 Series Control

Two isolated control circuits are executed for two frequency components controlling in series converter. The first one is 3rd harmonic control loop that used for DC voltage control. The DPFC control diagram of series converter is shown in Figure 4.9. The central control generates reference voltage for the series converters at the fundamental frequency to inject voltage in to the transmission line and the other reference voltage is used at 3rd harmonic frequency to keep the DC capacitor voltage of series converter.

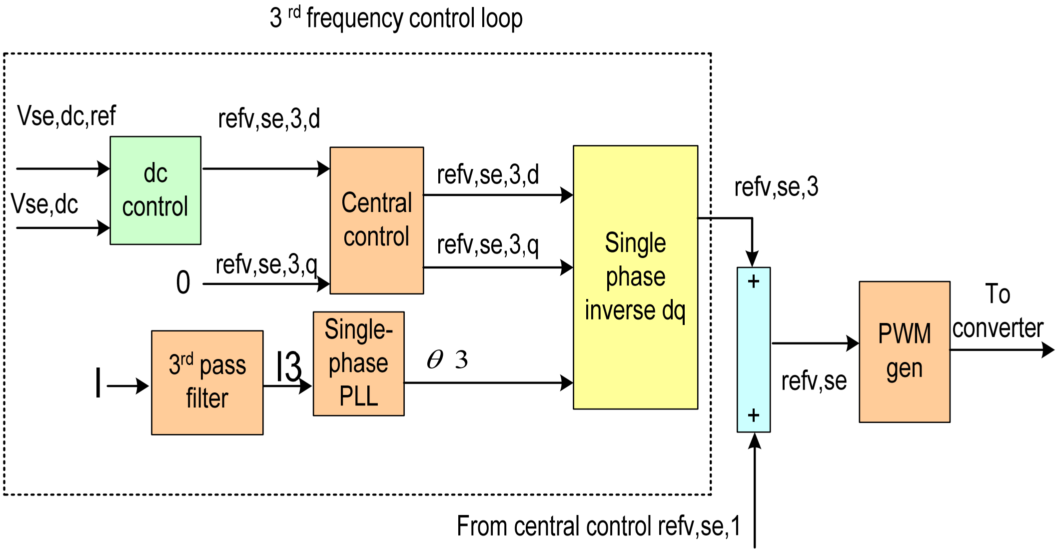


Figure 4.9: Series converter control block diagram.

The 3rd harmonic current that flows through the transmission line is captured by 3rd band pass filter. From the 3rd harmonic current the single-phase Phase Locked Loop

PLL produces a rotation reference frame. The DC voltage control loop generate control signal. The DC voltage controlled by d-component for 3rd harmonic voltage. As the q-component will cause reactive power injection into the network, it is kept at zero during the operation. As the current is taken for rotating reference frame for Park's transformation, by projecting the current to itself, the q-components $I_{1,q}$ and $I_{3,q}$ that are perpendicular to the current will be zero and Eqn.(4.15) can be written as:

$$C_{se}\frac{dV_{DC,se}}{dt}=\frac{1}{2}\left(ref_{v,se,1,d}I_{1,d}+ref_{v,se,3,d}I_{3,d}\right) \tag{4.19}$$

CHAPTER FIVE

SIMULATION AND RESULTS

5.1 Introduction

In this chapter, the performance evaluation of DPFC is verified in SIMULINK/MATLAB through implementation of DPFC and simulation it at different operating conditions. Firstly, the model of DPFC is simulated under a steady-state analysis. Simple two bus system is implemented with two voltage source blocks interconnected through L series branch blocks representing transmission line. The device and its controls are also developed in SIMULINK. It is observed from steady-state simulation results that shunt and series converters exchange power and the device is able to control power flow through the line. Secondly, the power quality improvement by using DPFC controller is developed and verified dynamically by connecting this device to RLC load through two transmission lines connecting in parallel and it observed that voltage sag and current swell can be mitigated effectively by using DPFC controller.

5.2 Steady-State Analysis

Distributed Power Flow Controller model of the simple two-bus system is designed by using MATLAB/Simulink software and the simulation results are discussed and presented. The model comprises a shunt converter and multi-series converters which are of a single phase. The shunt converter is placed in between the neutral point of the Δ-Y transformer and the ground, and it is power is supplied by the constant DC source. The results show the steady-state behavior with and without DPFC. The phase difference between buses is provided to obtain the power flow between them.

5.3 Network Simulation Model Without DPFC

Figure 5.1 depicts the simulation model without DPFC, the system consists of two three-phase sources interconnected via a Δ-Y transformer and a transmission line. The three inductors that coupled between buses B2 and B3 represent the transmission line. These two three-phase sources represent different distribution networks of two different areas connected together by the transmission line. The power flows from sending end to receiving end can get by ensuring the phase difference between buses. The active power and the reactive power are measured by the power measurement block based on the Equation 4.1.

The measurement block is shown in Figure 5.1 and Table 5.1 presents the parameter values that are substituted in the equation to obtain theoretical values.

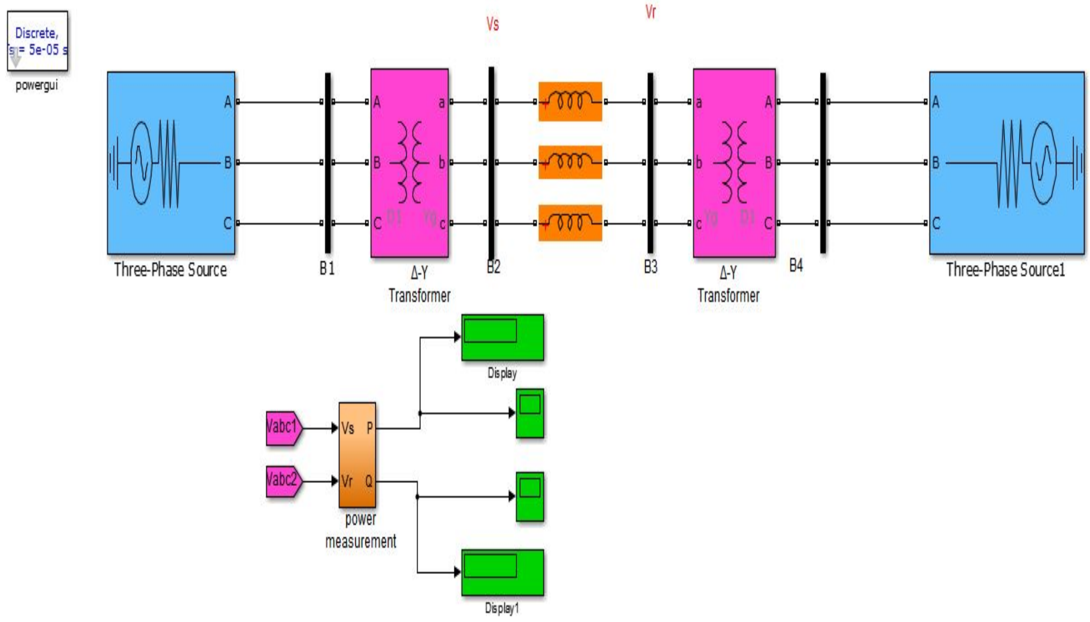


Figure 5.1: MATLAB/simulink model of system without DPFC**.**

The network values are given in Table 5.1.

Table 5.1: System constraints in simulink model.

Abbreviation	**Explanation**	**Value**
V_s	End bus Sending voltage	380 Volt
V_r	End bus Receiving voltage	380 Volt
Θ	Transmission angle between sending end bus voltages and receiving end bus voltages	1^{o} and90^{o}
L	Line inductance	6 mh

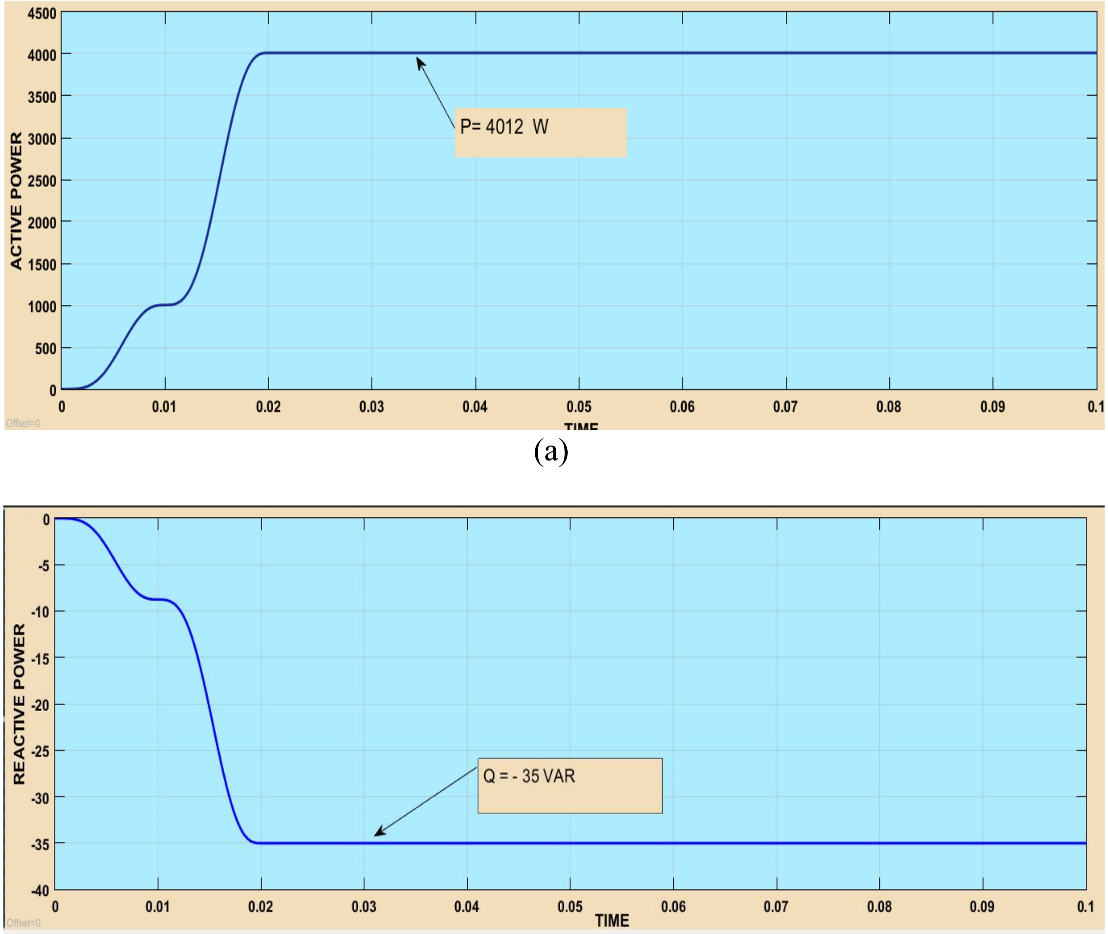
Figure 5.2 displays the simulation results obtained for the active and reactive power flows for 1 degree transmission angle. The theoretical values are calculated for 1-degree transmission angle using equation 4.2 and the resulting waveforms are depicted in Figures: 5.2 (a) and 5.2 (b).

In mathematical calculations the value of XL=(2 π fl)=$(2 * \pi * 50 * 6 * 10^{-3})$ =0.6 π

$$P_{R0} + jQ_{R0} = V_R \cdot \left(\frac{V_S - V_R}{JX_1}\right)^*$$

$$= 3 * 380 * \left(\frac{380\angle 1 - 380\angle 0}{J * (0.6\pi)}\right)^*$$

$$= (4011 - j35.02)VA \tag{5.1}$$



(a)

(b)

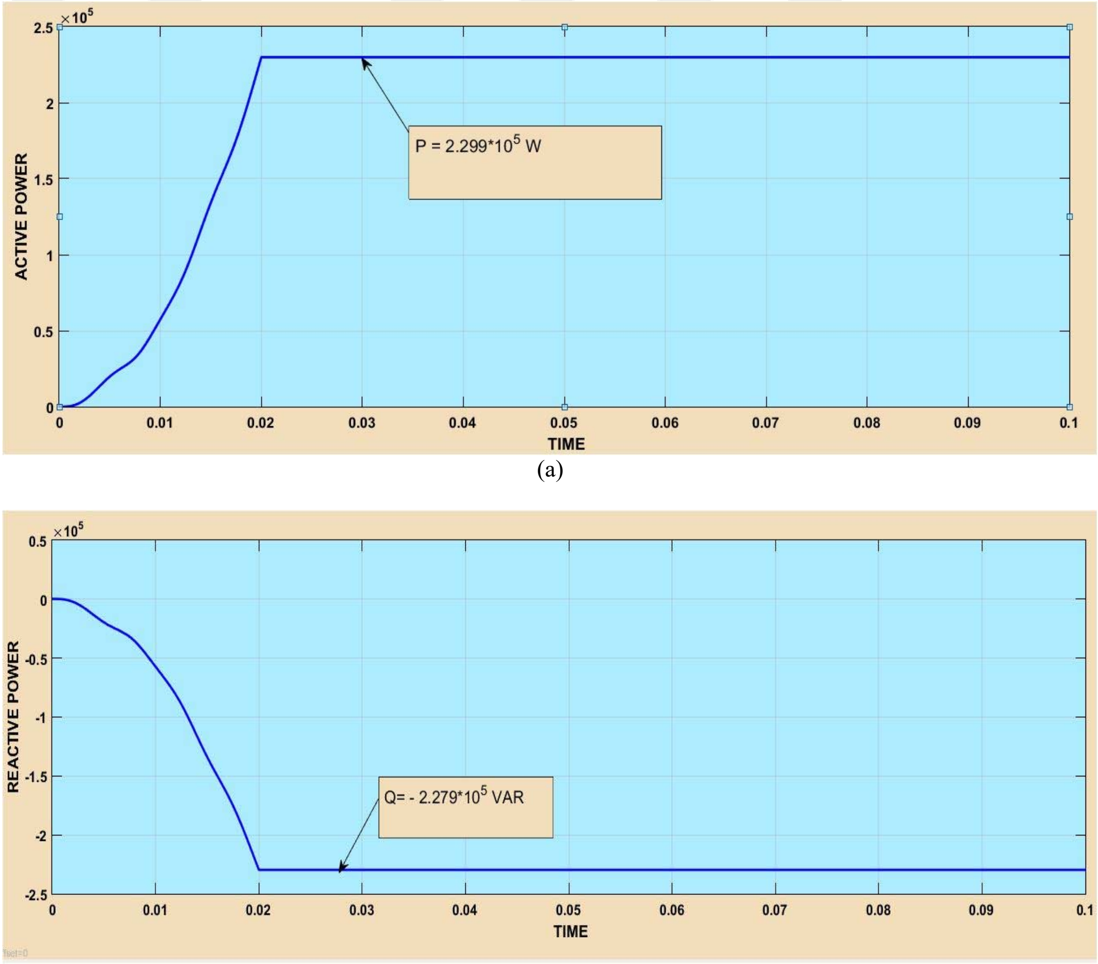
Figure 5.2: Power flows through the transmission line with out dpfc with 1 degree transmission angle (a) Active power (b) Reactive power.

The resulting wave for simulation shows the values of active and reactive power flows that observed from Figure 5.2 are (P= 4012 W and Q=35.02 VAR) for the system under study without DPFC for constraints with 1-degree transmission angle. Similarly, for the transmission angle of 90° the theoretical values and simulated waveforms are shown in Eqn. (5.2) and Figures 5.3 (a) and 5.3 (b).

$$P_{R0} + jQ_{R0} = V_R \cdot \left(\frac{V_S - V_R}{JX_1}\right)^*$$

$$= 3 * 380 * \left(\frac{380\angle 90 - 380\angle 0}{J * (0.6\pi)}\right)^*$$

$$= (2.29819 * 10^5 - j2.29819\ 10^5)\text{VA} \qquad (5.2)$$



(a)

(b)

Figure 5.3: Power flows through the transmission line with Out DPFC With 90 degree transmission angle (a) Active power (b) Reactive power.

The resulting wave for simulation shows the values of active and reactive power flows that observed from Figure 5.3 are ($P = 2.299 * 10^{-5}$ W and $Q = 2.297 * 10^{-5}$VAR) for the system under study without DPFC for constraints with 90 degree transmission angle.

5.4 Network Simulation Model with DPFC

The DPFC model with it´s control circuits will be added to the previous model of the network without DPFC which was shown in Figure 5.1. To control power flow in this system and to study the performance of this device, two cases of analysis will be used firstly by using two series converters per phase and then by using three series converters per phase. The goal of using a different number of series converters each time is to prove control ability by using multi-single-phase converters instead of using one large three phase converter as in UPFC.

5.4.1 Power Flow Control by Using DPFC with Two Series Converters Per Phase

The system model with DPFC controller is given in Figure 5.4 in which DPFC comprises a single phase shunt converter placed between Δ-Y transformer's neutral point and the ground and six single phase serial converters.

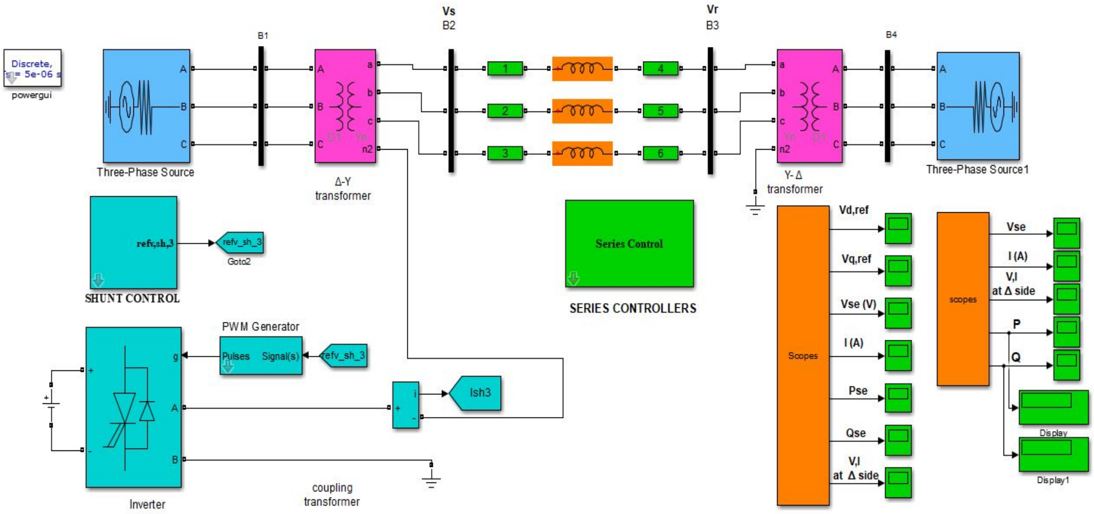


Figure 5.4: Simulation model of network using DPFC with two series converters per phase.

In this design there are six serial converters, each two converters are coupled in series with the transmission line in each phase on two sides of the inductor.In Figure 5.4 the series and shunt controls are shown as subsystems and the system specifications are tabulated in Table 5.1. From Figure 5.4 it is clear that the DC voltage source is coupled to the DC side of the inverter and the AC side is coupled via a coupling transformer to the system.

5.4.1.1 DPFC converter specifications

In DPFC the shunt and the series converters voltage and current ratings are depend on the control range of the DPFC. According to Eq 5.1 the minimum power flow with out DPFC connection is:

$$|Sr0| = |Pr0 + jQr0| = 4011 + (-j35.02)\ \text{VA} \quad \cong 4011\ VA \tag{5.3}$$

After DPFC connection the power flow according to Eq 5.12

$$|Src| = |Pr0 + jQr0| = 1805.84 + (-j35.0026) \cong 1805\ \text{VA} \tag{5.4}$$

the DPFC control range is given as:

$$|S,range| = |Src - Sr0| = |4011 - 1805| = 2206\ \text{VA} \tag{5.5}$$

When the DPFC control range is known, the total voltage at fundamental frequency injected by series converters can be calculated as following:

$$V_{se,1} = \left[\frac{(S_{range})jX_1}{V_r}\right]^* = \left[\frac{2206*50*2\pi*0.006}{380}\right]^* \cong 11\ \text{v} \tag{5.6}$$

The current that flows through the series converters is:

$$I_{se,1} = \left[\frac{|Srange| + |Sr0|}{\sqrt{3}\,V_r}\right]^* = \left[\frac{2206+4011}{\sqrt{3}*380}\right]^* \cong 10\ \text{A} \tag{5.7}$$

To find the specifications of the converters at the 3rd harmonic frequency, the maximum active power that is exchanged between the converters is given by:

$$P_{se,1} = \frac{X_1|S_{r0}|}{|V_r|^2}\left|S_{range}\right| = \frac{50*2*0.006*\pi*|4011|}{|380|^2}|2206| \cong 116\ W \tag{5.8}$$

The 3rd harmonic current is chosen to be one third of the nominal line current at the fundamental frequency, which gives a constant value of I3 = 3 A per phase, consequently. The maximum voltage of the series converter at the 3rd harmonic will be:

$$V_{se,3\,\max} = \left[\frac{(p_{se,MAX})}{3*I_3}\right] = \frac{116}{3*3} = 12.8 \cong 13\,V \tag{5.9}$$

The 3rd harmonic current though the shunt converter is:

$$|\,Ish,3| = 3|I3| = 9\text{ A} \tag{5.10}$$

and the voltage of the shunt converter is given by:

$$|Vsh,3| = |Vse,3 + jX3|ise,3|=|13+j2*150*0.006*\pi*|9||=51.6V\cong 52\,V \tag{5.11}$$

Table 5.2: DPFC parameters in simulink model.

Parameter Name	**Parameter Symbol**	**unit**	**Parameter Value**
Maximum ac voltage of shunt converter	$V_{sh,\,max}$	volt	52
Maximum ac current of shunt converter	$I_{sh,\,max}$	ampere	9
DC source supply of shunt converter	$V_{sh,\,DC}$	volt	17.7
Reference current with 3rd harmonic that injected by the shunt converter	$I_{sh,\,ref,3}$	ampere	3
Maximum ac voltage of the series converter at line side	$V_{se,\,max}$	volt	11
Maximum ac current of the series converter at line side	$I_{se,\,max}$	ampere	10

Table 5.3: K_I & K_P values for DPFC shunt control and series control.

Current shunt control:	
Symbol	Parameter Value
K_I	0.01
K_P	0.9
Series converters DC control:	
Symbol	Parameter Value
K_I	95
K_P	0.22
R	0.22

5.4.1.2 Shunt converter and shunt control

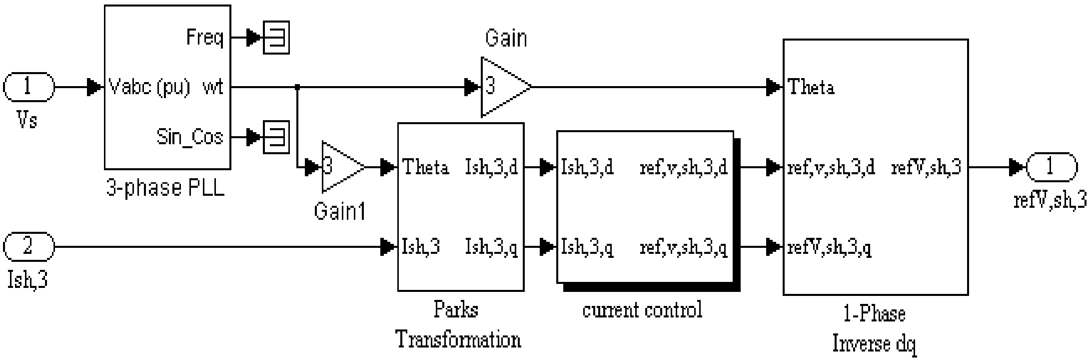


Figure 5.5: MATLAB simulation model for shunt control.

The simulation model of shunt control is shown in Figure 5.5. only 3rd harmonic frequency control is shown because the shunt converter DC voltage is maintained constant by DC source. A PLL-Phase Locked Loop is used to captures, three-phase frequency of bus voltage then the output signal is multiplied by 3 with gain block, thus creating a virtual rotation reference frame for third harmonic frequency. The control system is consisted of the current controller, park's and inverse park's transformer subsystem. Figure 5.6 shows the simulation model of each subsystem. PI-Proportion Integral controller is used to realize the current control gains which are tabulated in table 5.3.

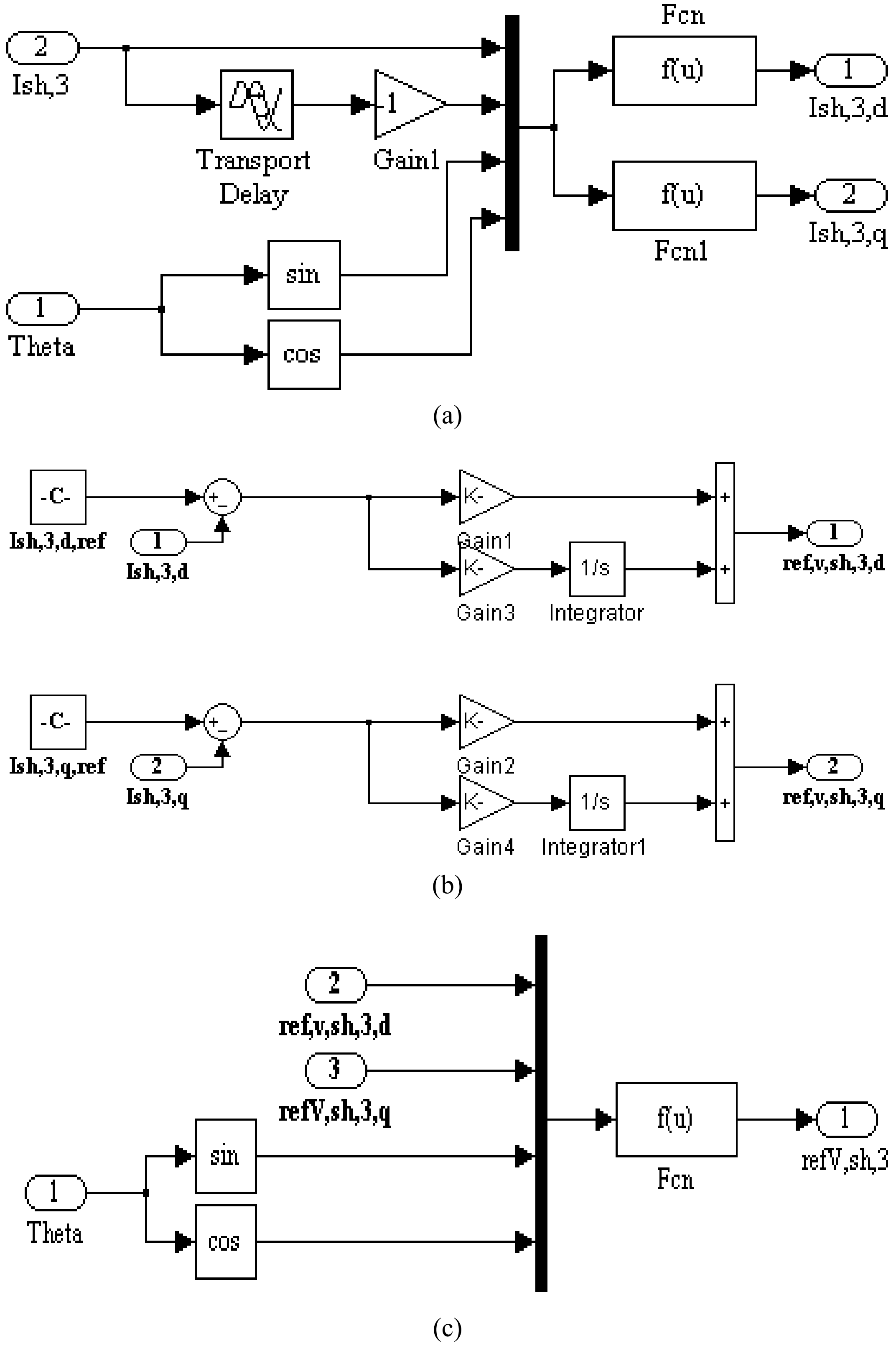


Figure 6.6: Shunt converter control: (a) Park's transformation (b) Current control (C) Inverse dq-transformation.

5.4.1.3 Series Converter and Series Control

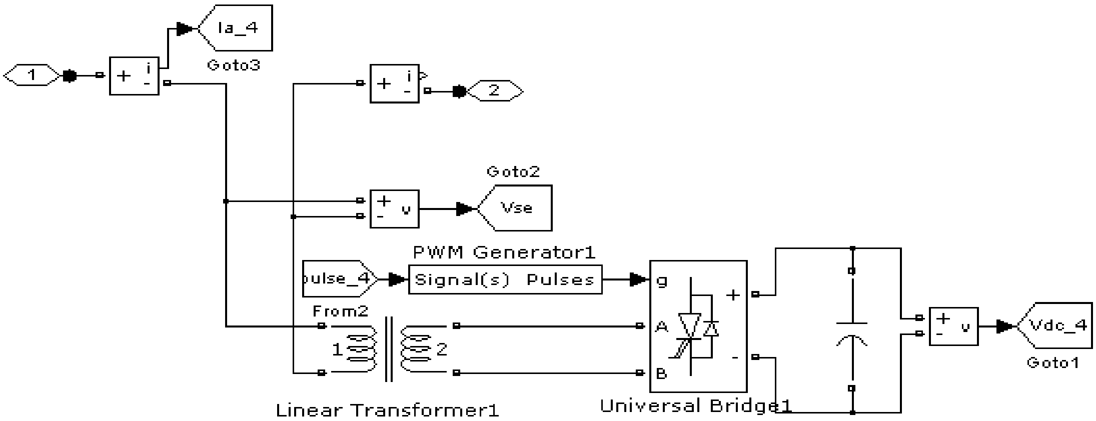
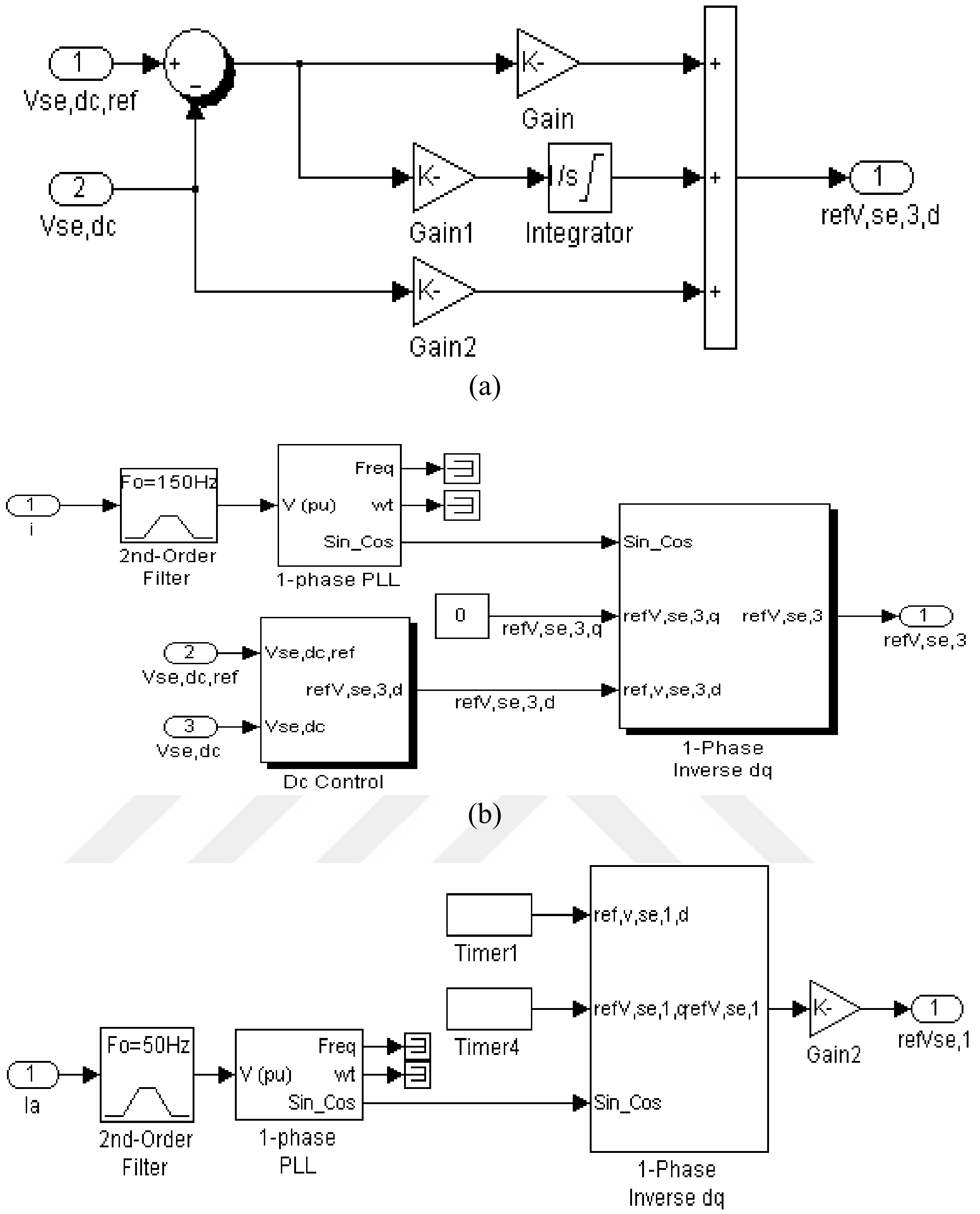


Figure 5.7: MATLAB / Simulation Model for Series Converters Control.

The single-phase series converter is a full bridge converter coupled with a capacitor that connected on DC side of the converter. It is coupled with transmission line by a single-phase transformer as shown in figure 5.7. Each one of series converters has its isolated control from others as own control whose simulation model is shown in Fig 5.8 (a). The DC control is depicted in 5.8 (b). The 3rd harmonic current is filtered from the line current by the second order filter block. The DC control gains calculated are tabulated in table 5.3. Figure 5.8 (c) shows the fundamental frequency control. The fundamental rotating reference frame is generated by filtering fundamental current with second-order filter.



(a)

(b)

(c)

Figure 5.8: Block diagram for series converter control: (a) DC control (b) 3rd Harmonic frequency control (c) Fundamental frequency control.

5.4.2 Steady-State Analysis Results

To analyze steady state behavior of DPFC, the series converter is regulated to inject 2V of fundamental voltage. The results of the injected line current are given in Figure 5.9 and the injected voltage shown in Figure 5.10. Figure 5.11 shows the voltage and current waveforms of the transformer at Δ side. The shunt converter injects third harmonic constant current which is equally distributed over the three phases and overlaid on the fundamental current as shown in Figure 5.9. The voltage waveforms of the series converter injected are shown in Figure 5.10, which are shaped as a Pulse Width Modulation PWM waveform with two frequency components. The amplitude indicates the DC-capacitor voltage of the transformer at the line side.

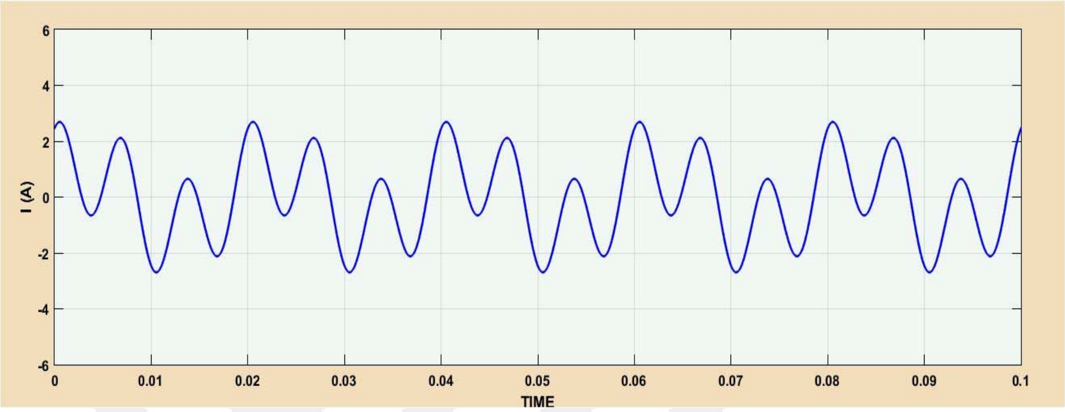


Figure 5.9: The line current in steady-state operation of DPFC.

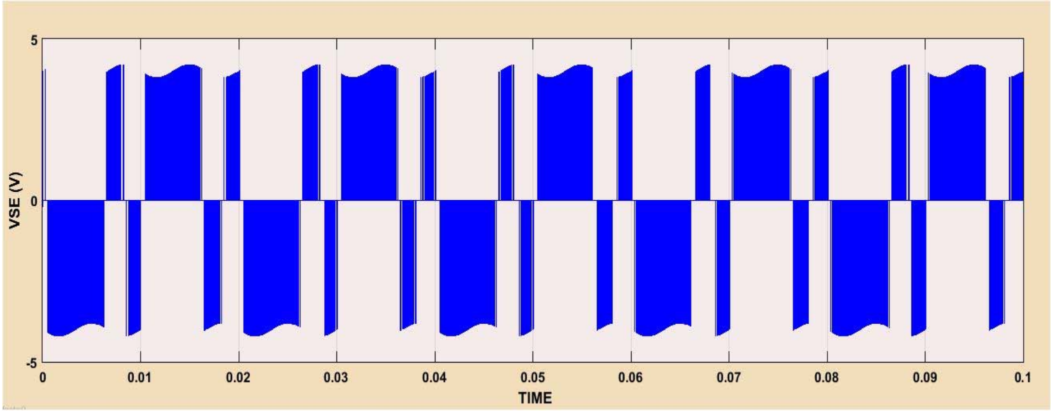


Figure 5.10: Series converter voltage in steady-state operation of DPFC.

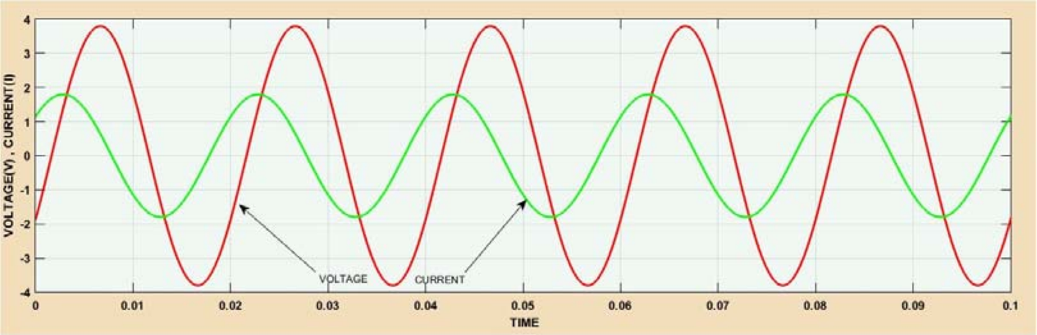
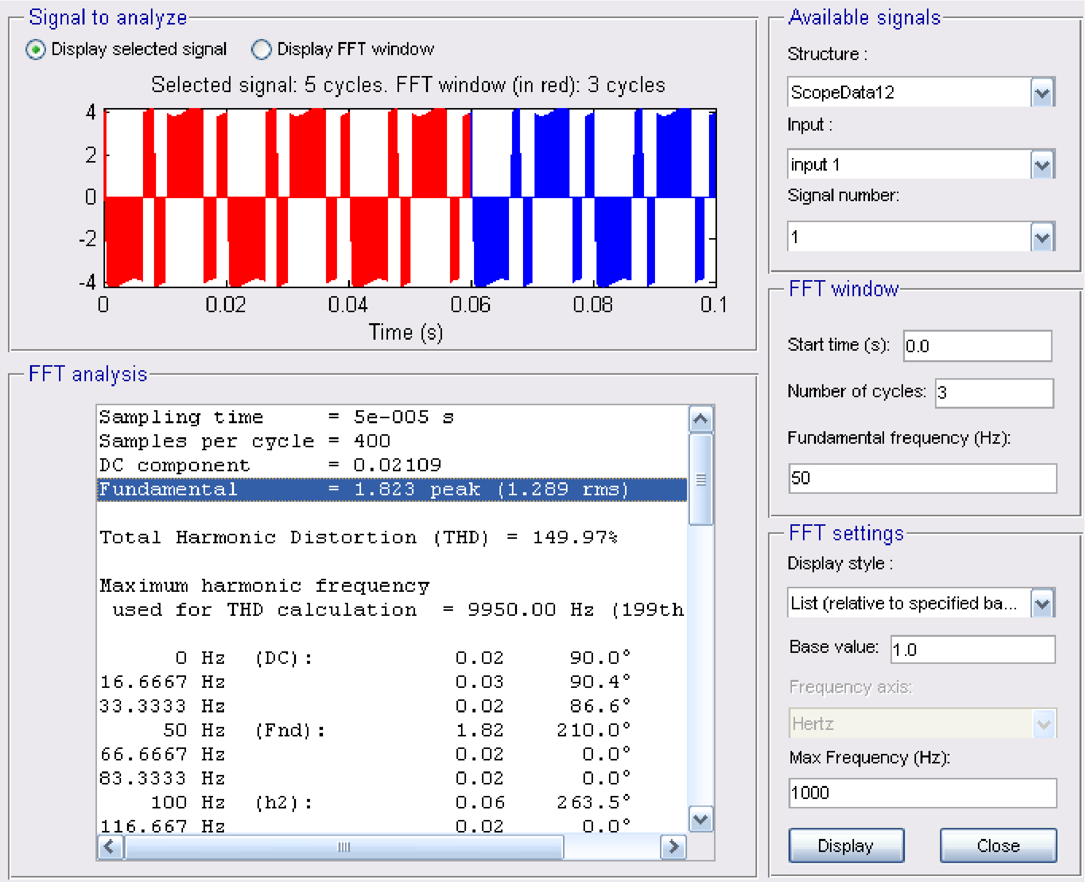


Figure 5.11: The bus voltage and current at the Δ side of the transformer in steady-state DPFC operation.

Figure 5.11 depicts waveforms of voltage and current without 3rd harmonic component. Thus, the property of 3rd harmonic filtering is observed. The FFT analysis of converter voltage is shown in Figure 5.12.



● Display selected signal

Selected signal: 5 cycles. FFT window (in red): 3 cycles

FFT analysis

```
Sampling time       = 5e-005 s
Samples per cycle = 400
DC component        = 0.02109
Fundamental         = 1.823 peak (1.289 rms)

Total Harmonic Distortion (THD) = 149.97%

Maximum harmonic frequency
 used for THD calculation   = 9950.00 Hz (199th

       0 Hz   (DC):            0.02      90.0°
16.6667 Hz                     0.03      90.4°
33.3333 Hz                     0.02      86.6°
      50 Hz   (Fnd):           1.82     210.0°
66.6667 Hz                     0.02       0.0°
83.3333 Hz                     0.02       0.0°
     100 Hz   (h2):            0.06     263.5°
116.667 Hz                     0.02       0.0°
```

Structure : ScopeData12

Input : input 1

Signal number: 1

Start time (s): 0.0

Number of cycles: 3

Fundamental frequency (Hz): 50

Display style : List (relative to specified ba...

Base value: 1.0

Max Frequency (Hz): 1000

Figure 5.12: FFT analysis of series converter voltage.

5.4.3 Power Flow Controllability By Using DPFC With Two Series Converters Per Phase

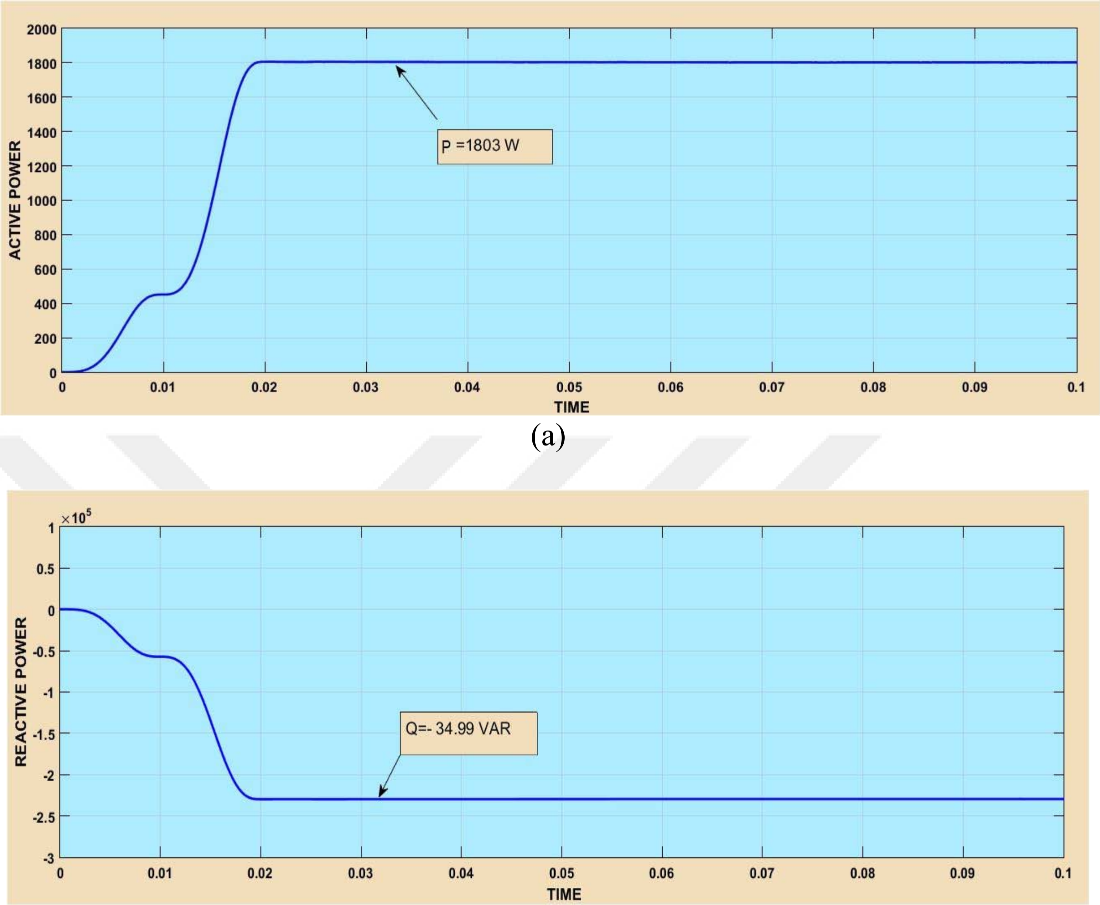
The mathematical values of the power flow for 1 degree and 90 degree transmission angles with six series converters are measured using equations (5.12) and (5.13) respectively, the theoretical calculations for 1 degree are:

$$S_R = P_R + jQ_R = V_R \cdot I_1^{\ *} = V_R \cdot \left(\frac{V_S - V_R - V_{Se1}}{JX_1}\right)^*$$

$$= 3 * 380 * \left(\frac{380\angle 1 - 380\angle 0 - 3.646\angle 90}{J * (0.6 * \pi)}\right)^*$$

$$= (1805.84 - j35.0026)\ \text{VA} \qquad (5.12)$$

The waveforms with simulation values of active power and reactive power with DPFC compensation for 1 degree angles are shown in Figure 5.13.



(a)

(b)

Figure 5.13: Power flow control with 1° transmission angle by using DPFC with two converters per phase (a) The transmission line active power (b) The transmission line reactive power**.**

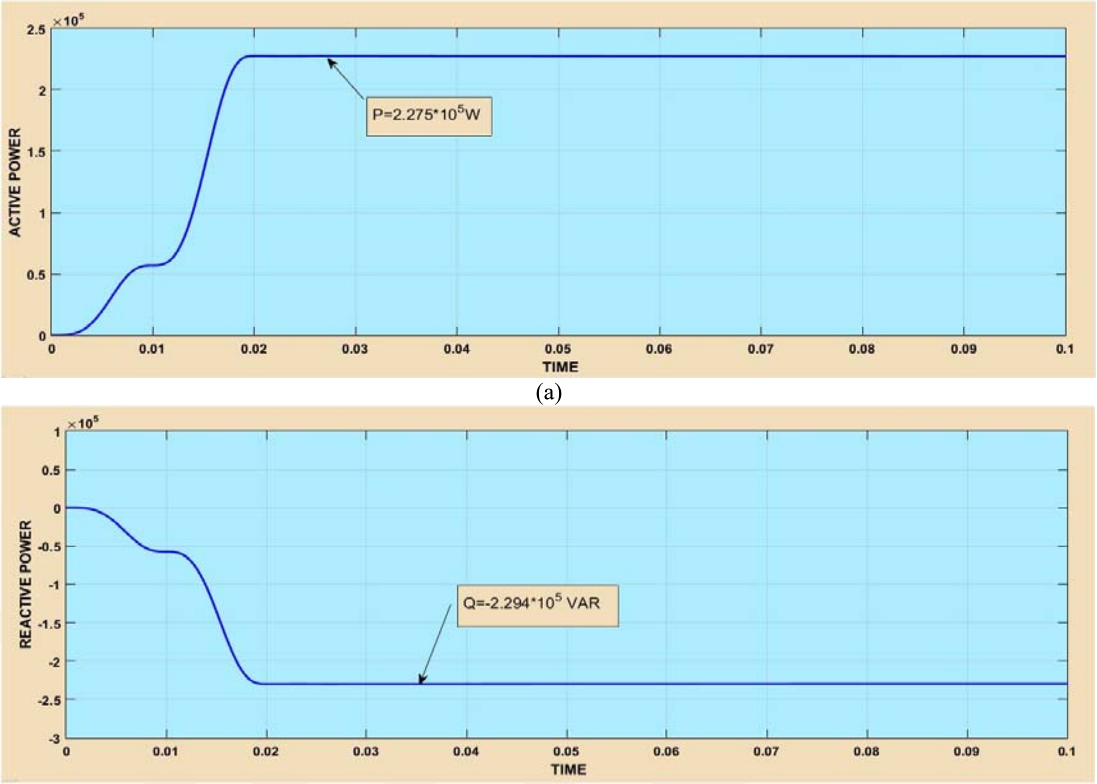
The theoretical calculations for 90 degree are:

$$S_R = P_R + jQ_R = V_R \cdot I_1{}^* = V_R \cdot \left(\frac{V_S - V_R - V_{Se1}}{JX_1}\right)^*$$

$$S_R = 3 * 380 * \left(\frac{380\angle 90 - 380\angle 0 - 3.646\angle 90}{J * (0.6 * \pi)}\right)^*$$

$$= (2.27614 * 10^5 - j2.29819 \quad * 10^5)\ \text{VA} \qquad (5.13)$$

The waveforms with simulation values of active power and reactive power with DPFC compensation for 90 degree angle is shown in Figure 5.14.



(a)

(b)

Figure 5.14: Power flow control with 90° transmission angle by using DPFC with two converters per phase (a) The transmission line active power (b) The transmission line reactive power.

5.4.4 Power Flow Controllability by Using DPFC With Three Series Converters Per Phase

In this design there are nine serial converters, each three converters are coupled in series with the transmission line in each phase on two sides of the inductor as shown in figure 5.15.

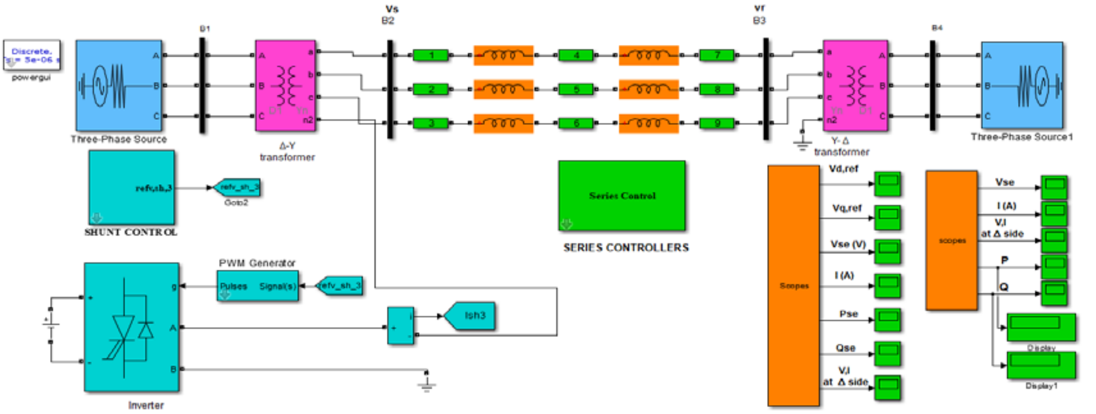
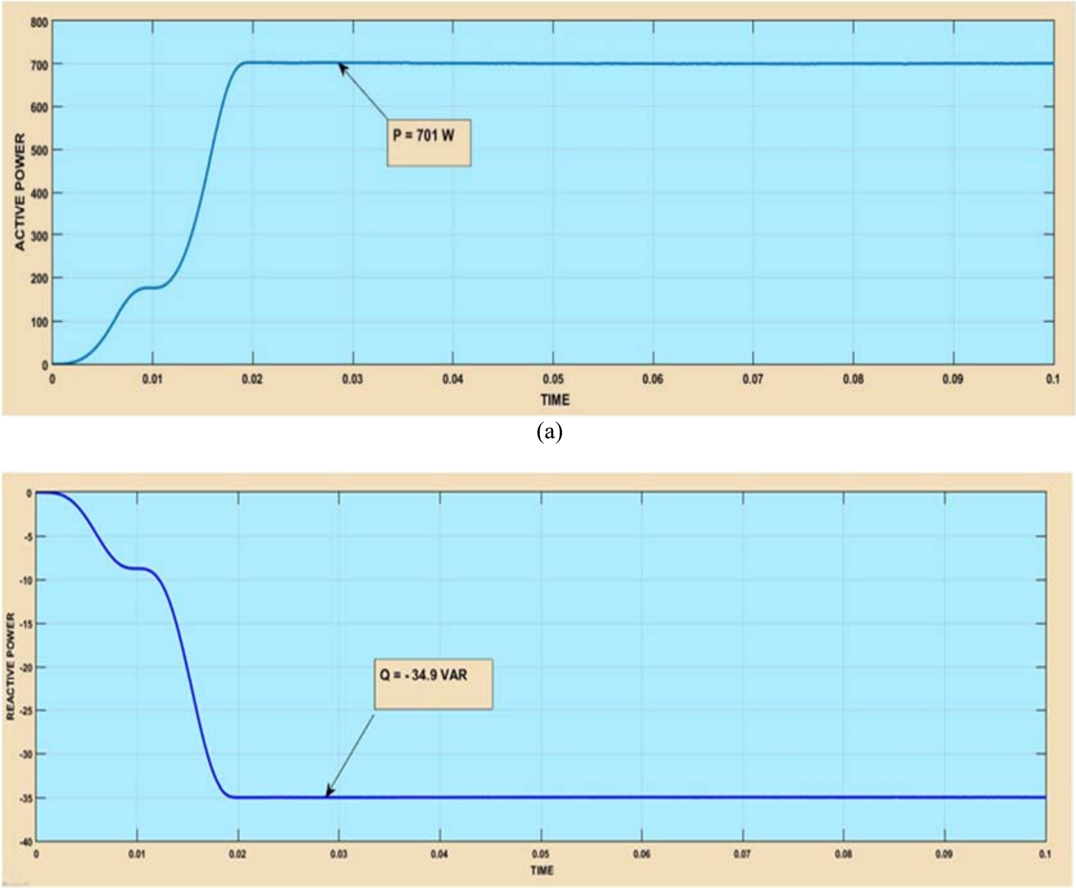


Figure 5.15: Simulation model of network using DPFC with three series converters per phase.

The mathematical values of the power flow for 1 degree and 90 degree transmission angles with nine series converters are measured using Equations 5.14 and 5.15 respectively, the theoretical calculations for 1 degree are:

$$
\begin{aligned}
S_R &= P_R + jQ_R = V_R \cdot I_1^{*} = V_R \cdot \left(\frac{V_S - V_R - V_{Se1}}{JX_1}\right)^{*} \\
&= 3 * 380 * \left(\frac{380\angle 1 - 380\angle 0 - 5.47\angle 90}{J * (0.6 * \pi)}\right)^{*} \\
&= (702.712 - j35)\ \mathrm{VA} \qquad (5.14)
\end{aligned}
$$

The waveforms with simulation values of active power and reactive power with DPFC compensation for 1 degree angles are shown in Figure 5.16



(a)

(b)

Figure 5.16: Power flow control with 1° transmission angle by using DPFC with three series converters per phase (a) The transmission line active power (b) The transmission line reactive power.

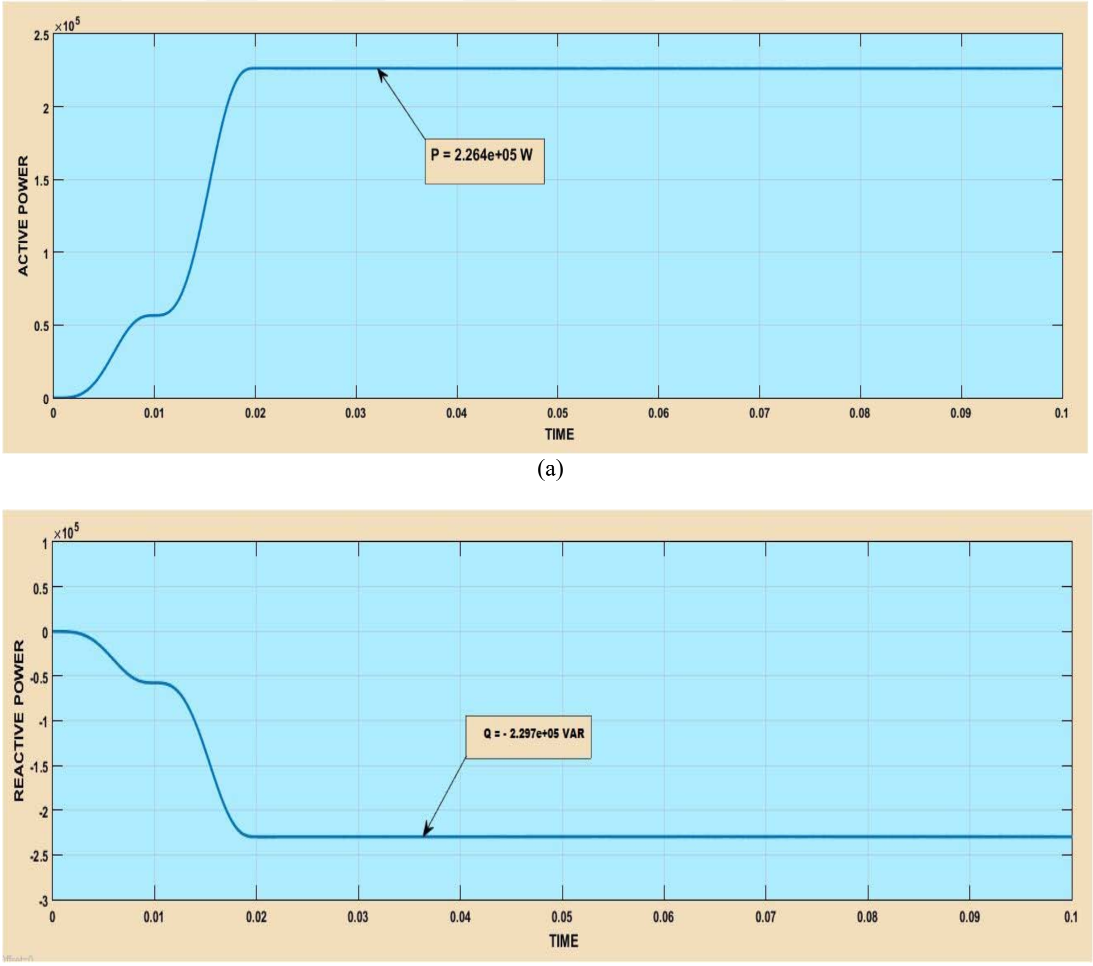
The theoretical calculations for 90 degree are:

$$S_R = P_R + jQ_R = V_R \cdot I_1^{\,*} = V_R \cdot \left(\frac{V_S - V_R - V_{Se1}}{JX_1}\right)^{*}$$

$$S_R = 3 * 380 * \left(\frac{380\angle 90 - 380\angle 0 - 5.47\angle 90}{J * (0.6 * \pi)}\right)^{*}$$

$$= (226511 - j229819.7)\ \text{VA} \tag{5.15}$$

The waveforms with simulation values of active power and reactive power with DPFC compensation for 90 degree angle are shown in Figure 5.17.



(a)

(b)

Figure 5.17: Power Flow Control With 90° Transmission Angle By Using DPFC With Three series Converters Per Phase (a) The Transmission Line Active Power (b) The Transmission Line Reactive Power**.**

Table 5.4 compares the theoretical values that are calculated and the values that obtained from simulation of active and reactive power flow for (1) degree and (90) degree transmission angles with and without DPFC compensation.

Table 5.4: Comparison between the theoretical values with obtained values from the simulation.

Power Flows Without DPFC Compensation		
	Calculated Value	Measured Value
With 1-degree transmission angle		
Active power (P_{ro})(watt)	4011	4012
Reactive power (Q_{ro})(var)	-35.02	-34.99
With 90-degree transmission angle		
Active power (P_{ro})(watt)	229819	229900
Reactive power (Q_{ro})(var)	-229819	-227900
Power Flows with DPFC Compensation by Using Six Series Converters		
	Calculated Value	Measured Value
With 1 degree transmission angle		
Active power (P_r)(watt)	1805,84	1803
Reactive power (Q_r)(var)	-35.002	-34.99
With 90 degree transmission angle		
Active power (P_r)(watt)	227614,7	227500
Reactive power (Q_r)(var)	-229819.737	-229400
Power Flows with DPFC Compensation by Using Nine Series Converters		
	Calculated Value	Measured Value
With 1 degree transmission angle		
Active power (P_r)(watt)	702.712	701
Reactive power (Q_r)(var)	-35	-34.9
With 90 degree transmission angle		
Active power (P_r)(watt)	226511	226400
Reactive power (Q_r)(var)	-229819.7	-229700

The resulting from the values obtained in the previous table shows that the DPFC has the ability to control power flow in transmission system effectively and this ability is increased by increasing the number of series converters per phase.

When comparing the values of the real power before DPFC connecting and its values after DPFC connection, it is noted that the DPFC is able to reduce the minimum power flow obtained by using 1-degree transmission angle from 4.012 kW without DPFC connection to 1.803 kW by using DPFC with two series converters Per Phase and to 0.701 kW by using DPFC with three series converters per phase.

For 90-degree transmission angle, the DPFC is able to reduce maximum power flow from 229.9 kw without DPFC connection to 227.5 kW by using DPFC with two series converters Per Phase and to 226.4 kW by using DPFC with three series converters per phase. The results obtained depend on the DPFC control range in the power system.

As shown in the Table 5.4, the measured values of active and reactive power flow are approximately equal to the calculated values according to equations.

5.5 Step Response Results

To control the transmission line power flow and to prove the ability of DPFC to control power flow a step change is made at the reference voltage of the serial converters Figure 5.18 explain the step response of the Simulink model. The step change contains both active and reactive change as shown in figure 5.18. The result shows that the DC voltage of the series converter is stabilized before and after the step change as shown in Figure 5.19. The current through the line is shown in Figure 5.20. Figure 5.21 shows the ability of series converter to absorb and inject active and reactive power before and after step change at fundamental frequency to the grid. The results show that the series converters have ability to absorb and inject both active and reactive power to the grid at the fundamental frequency. As shown in Figure 5.20. It is observed that the change in the voltage injected by the series converter changes the current flowing through the line.

(a)

(b)

Figure 5.18: The series converters reference voltage (a) V,D , (b)V,Q.

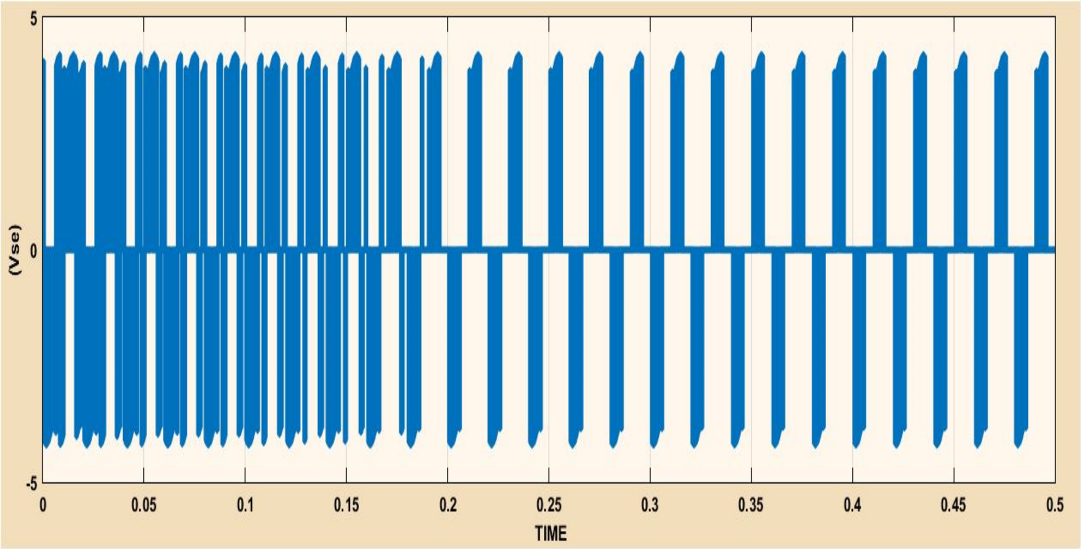


Figure 5.19: DPFC series converter voltage at step response.

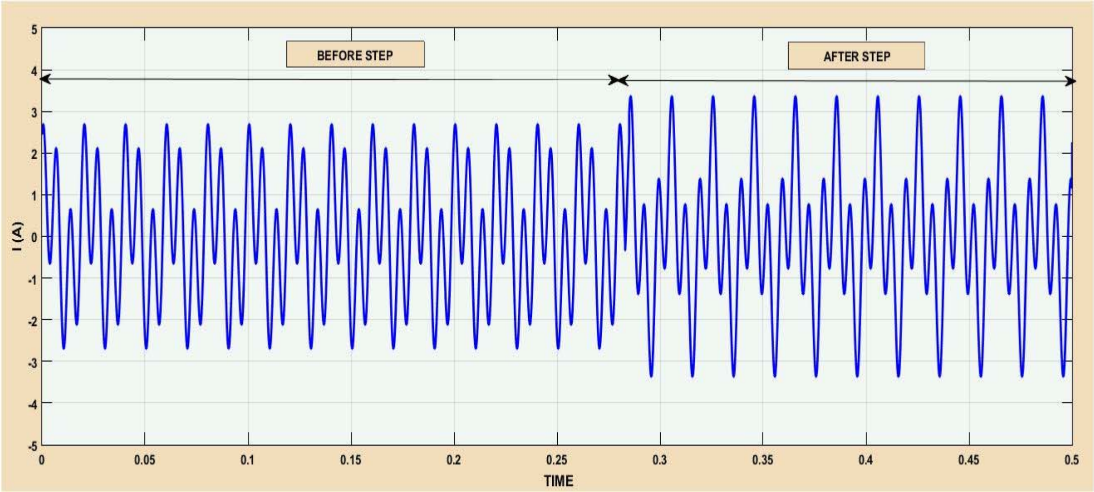


Figure 5.20: line current at step response of the DPFC.

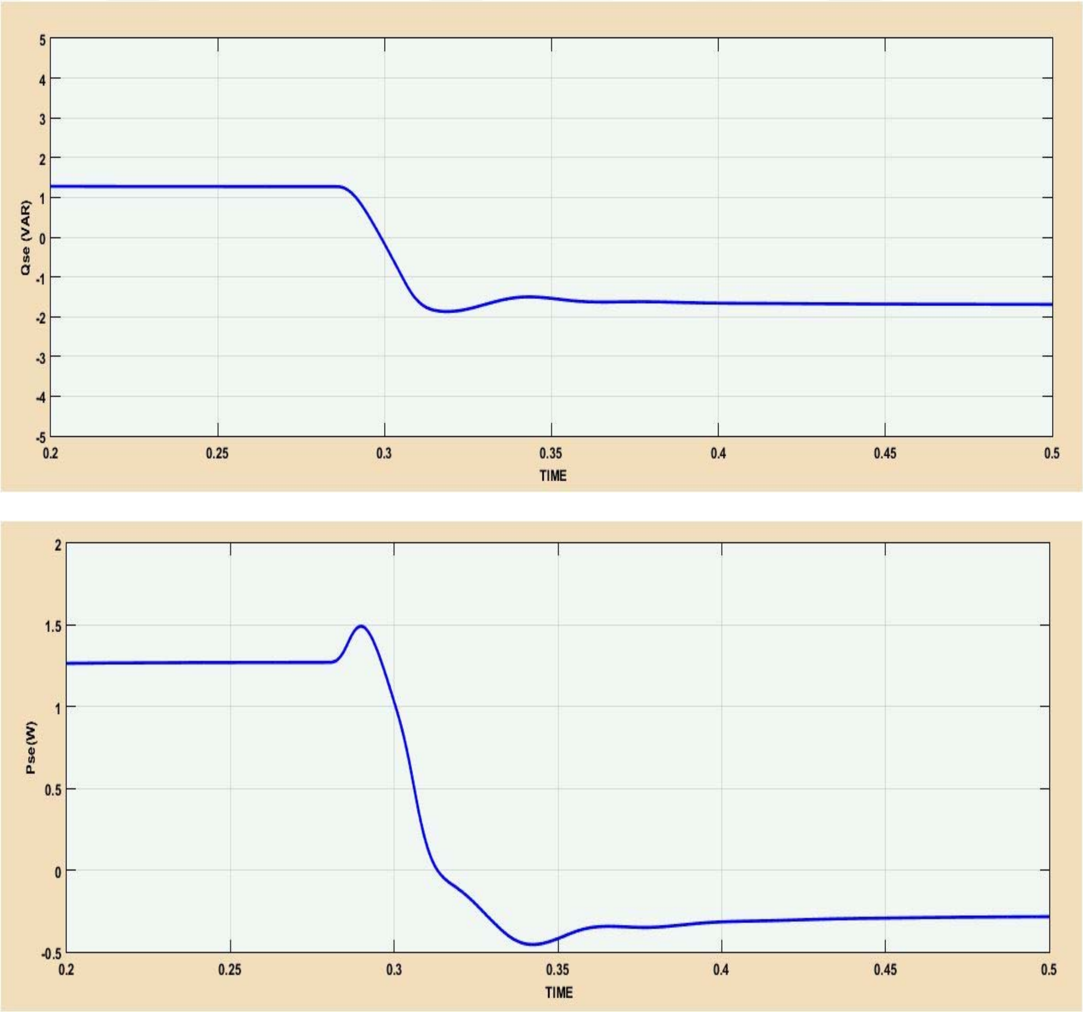


Figure 5.21: Active and reactive power injected by series converter at the fundamental frequency through the step response.

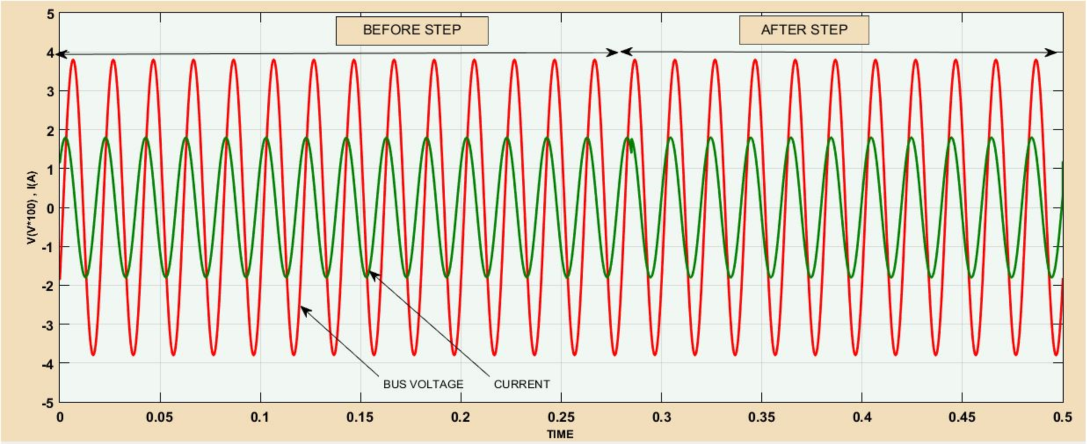


Figure 5.22: Bus voltage and current at the (Δ) side of the transformer at step response of the DPFC.

From Figure 5.22 it is clear that there is no 3rd harmonic component at transformer Δ-side of the network and a phase shift of the current is observed in waveforms.

5.6 Dynamic Performance of DPFC

The power system under study is shown in Figure 5.23. It consists of RLC load connected to the three-phase source by parallel transmission lines TL1, TL2 these two transmission lines have same parameters and same length. The power flow controller´s shunt converter is connected to the system in TL2 by three-phase transformers and the series converters are distributed through the transmission line. The dynamic performance for DPFC is simulated by using MATLAB/Simulink by applying three-phase fault near the load side.

Table 5.5: Parameters of power system under study.

Parameters	Value
3-phase source rated Voltage	132 KV
3-phase source rated power	100 MW
3-phase source frequency (HZ)	60 HZ
Transmission Line length	100 KM
Transmission Line resistance	0.012 ohm / KM
Transmission Line inductance	0.9337 mh / KM
Transmission Line capacitance	12.74 μf/KM
DC capacitor link	600 µF
Coupling Transformer(shunt) Nominal power	100 MVA
Coupling Transformer(shunt) Voltage	220/15(KV)
Fault Type	ABC-G
Fault Ground resistance	0.01 (OHM)

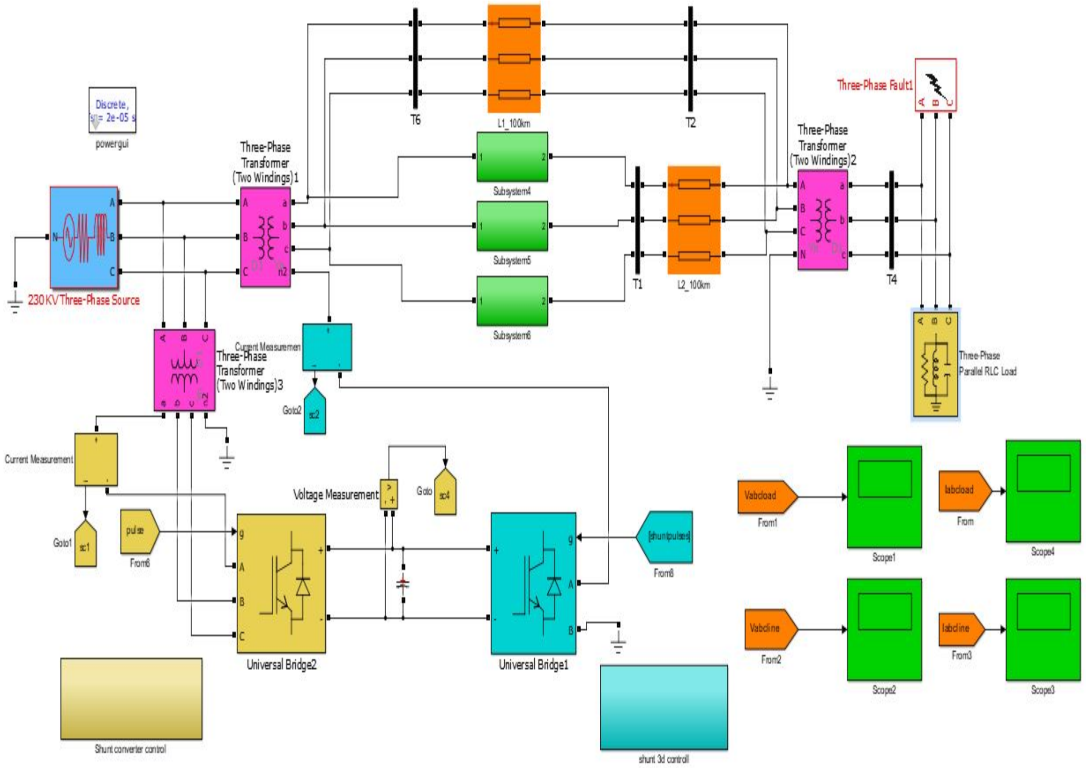


Figure 5.23: Simulation model for the power system with DPFC.

The fault takes time duration between (0.1 and 0.2) second. During the fault occurrence, there is sag occurs in load voltage and causes the voltage to reduce from (0.83 % to 0.53%) this difference magnitude is about 0.3% from normal pu value as shown in Figure 5.24. And as a reaction to this fault, there is a swell in a current wave, this swell causes current to raise from (0.28% to 0.57%) per unit. This difference magnitude is about (0.29%) pu from normal value of current.

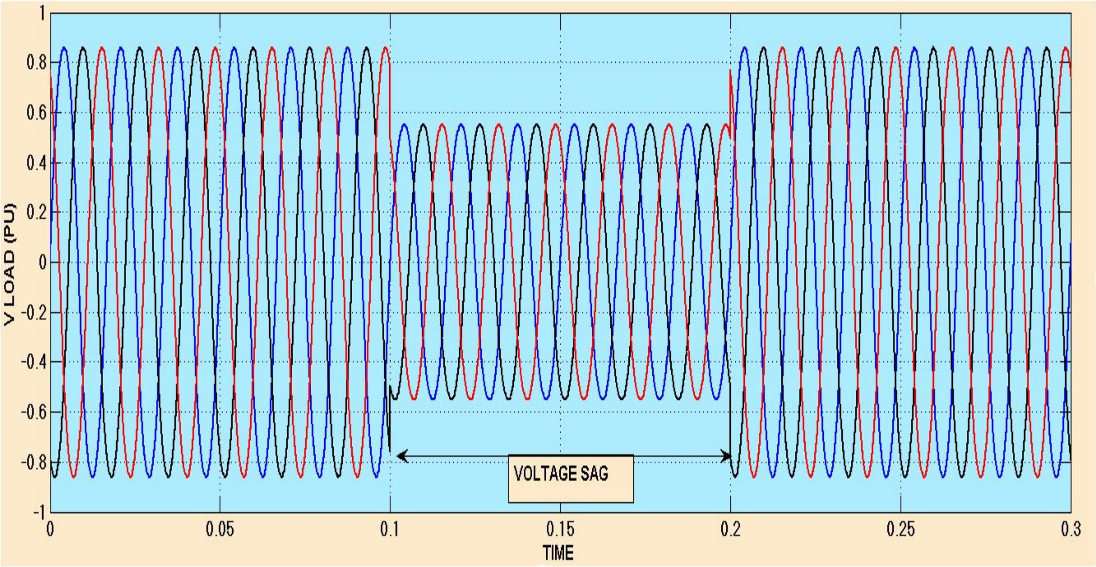


Figure 5.24: Voltage sag waveform without DPFC connection during the fault condition.

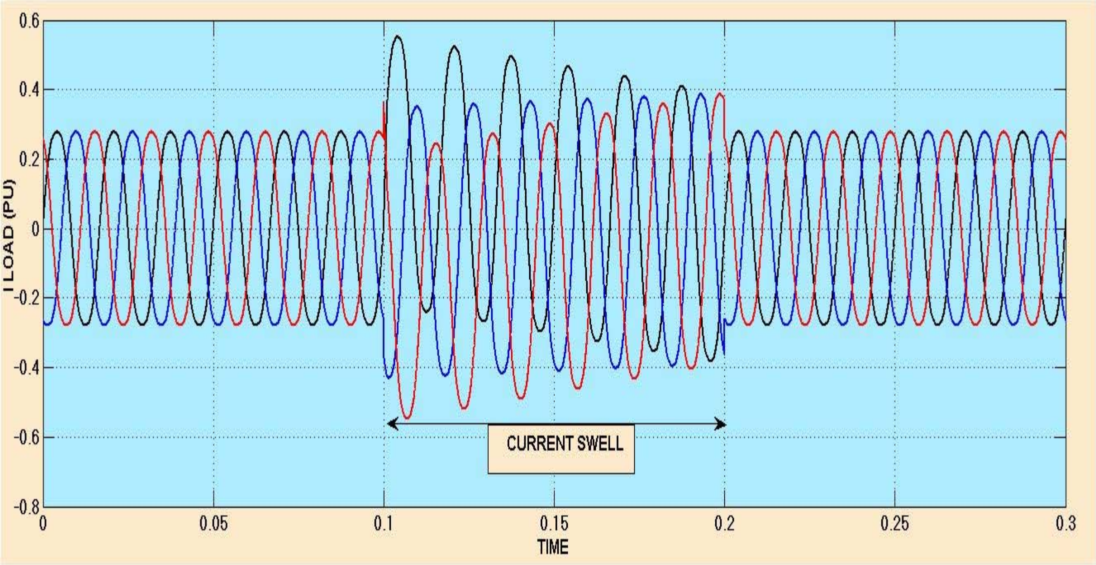


Figure 5.25: Current swell waveform without dpfc connection during the fault condition.

After DPFC connection, the voltage sag and current swell can be mitigated to values near from normal values for voltage and current before fault happening as shown in Figure 5.26 and Figure 5.27.

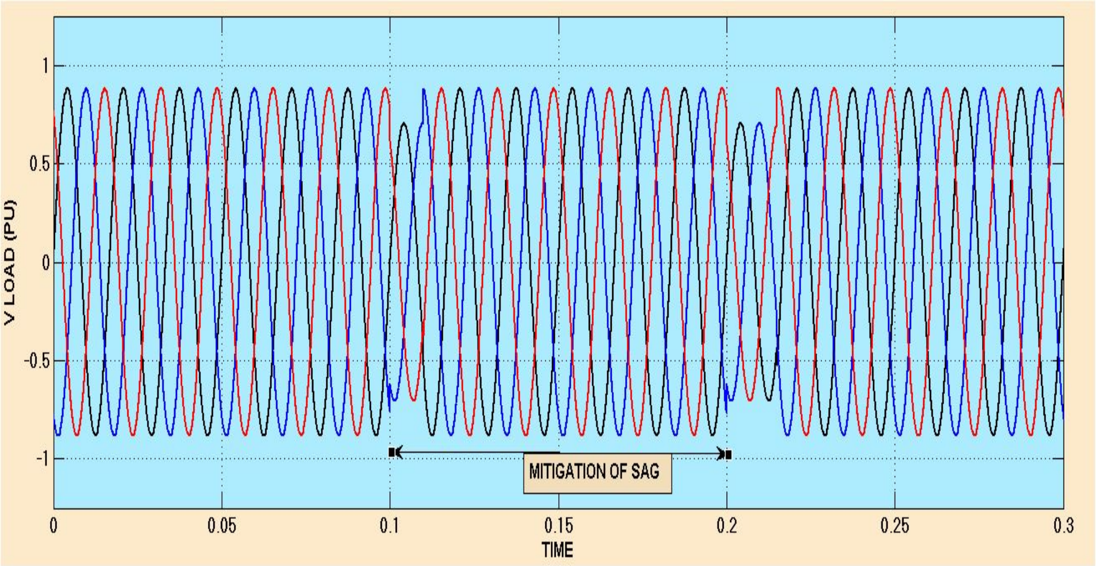


Figure 5.26: Voltage sag mitigation with DPFC compensation.

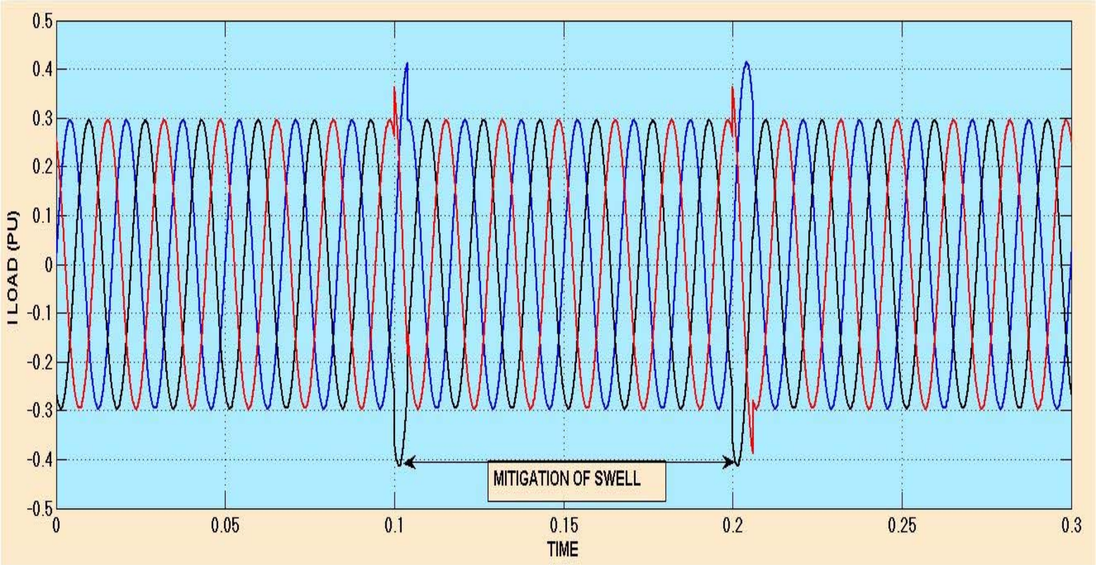


Figure 5.27: Current swell mitigation with DPFC compensation.

The load voltage harmonic analysis without DPFC connection can be seen in Figure 5.28 which is having a value equal to (3.23%) of THD.

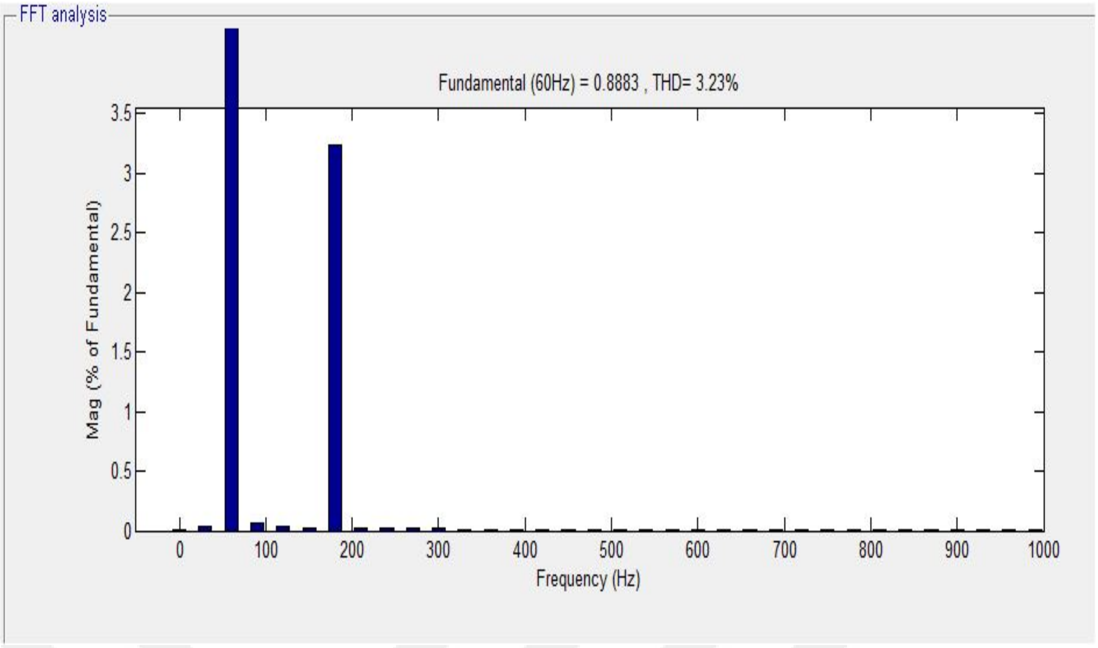


Figure 5.28: Total harmonic distortion of load voltage without DPFC connection.

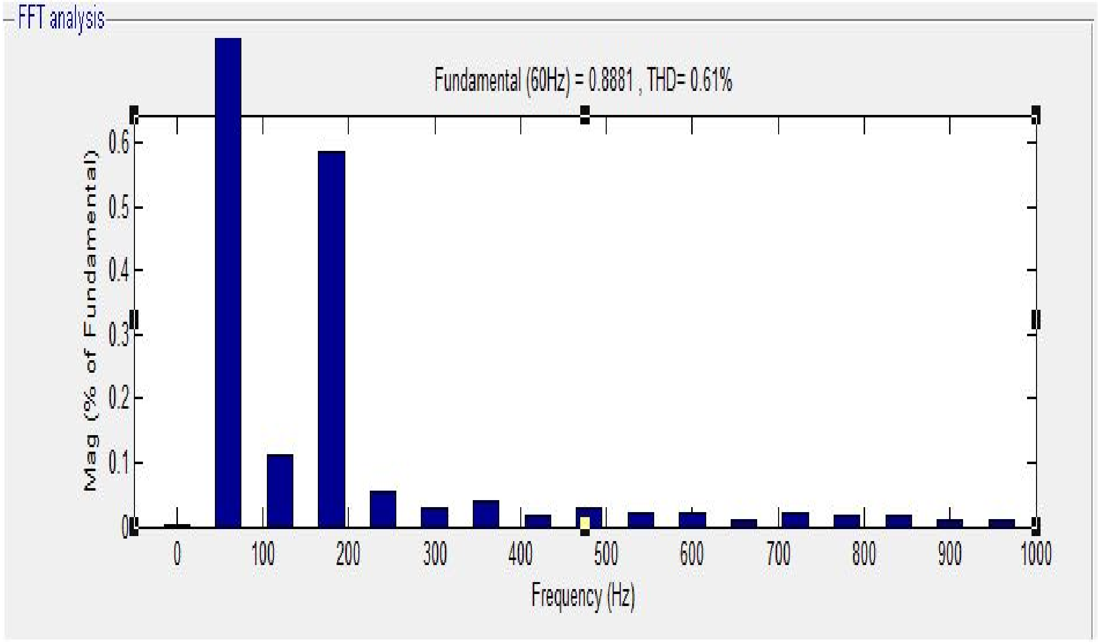


Figure 5.29: Total harmonic distortion of load voltage with DPFC connection.

After DPFC connection and disturbances mitigation, the THD is reduced to (0.61%). It is clear from these results that harmonic is eliminated to acceptable value with DPFC connection to the power system.

CHAPTER SIX

CONCLUSION

6.1 Conclusion

The DPFC is one of the FACTS devices which has been recently developed. In this study, the performance evaluation of DPFC device to control the power flow in the transmission system and to improve the power quality in the transmission system has been studied. The performance evaluation of DPFC is verified in SIMULINK by using MATLAB software through simulation of this device at different operating conditions.

Firstly, the model of DPFC is simulated under steady-state and step-response analysis. Simple two bus system is implemented with two voltage source blocks interconnected through RLC series branch blocks representing transmission line. The device and its control are also implemented in SIMULINK. The shunt and series converters in Simulink are realized using universal bridge block available in Simulink library and also the controllers are realized with blocks available in Simulink library. The shunt and series controls are implemented according to the DPFC modeling. The results show that voltage injected by series converter contains both fundamental and third harmonic frequency components. It is observed from the results that the series control steadies the level of the capacitor DC voltage of each converter and is also shown that the series converter can exchanges active and reactive power to the test system.

The results proved the device's ability to control power flow through the transmission line by connecting six converters and then nine series converters in the network. From the results can be observed that the control property increases with the increasing number of converters.

It is observed from step-response simulation results that shunt and series converters exchange power and the device is able to control power flow through the transmission line. Secondly, the power quality improvement by using DPFC controller is developed and verified dynamically by connecting this device to RLC load through two transmission lines connecting in parallel and it observed that voltage sag and current swell can be mitigated effectively by using DPFC controller. The results obtained from the simulation for this device proved that the performance of this device in the stage of transmission of electricity is excellent. Finally, the results proved that this device has the ability to control the flow of electrical energy with the difference in transmission angle. It has the ability to mitigate problems that cause disturbances to the electrical system with high efficiency.

6.2 Future Scope

Because of the principle of work for DPFC is based on using the third harmonic frequency to exchange power between shunt and series converters, the third harmonic current will cause extra losses in the transmission line and the transformers. In this thesis the third harmonic current is set as constant value by right adjusting of the amount of this current according to the amount of power that system requires the losses can be reduced. Also, using advanced soft computing control techniques to control DPFC converters is important to develop the performance of DPFC and the optimal location of DPFC in the power system network can be one of the future scopes for this device to give more enhance to the device working.

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