UNIVERSITY OF ÇUKUROVA
INSTITUTE OF NATURAL AND APPLIED SCIENCE

MSc THESIS

Lütfü SARIBULUT

PERFORMANCE ANALYSIS OF UNIFIED POWER FLOW CONTROLLER (UPFC) BY USING DIFFERENT CONTROLLERS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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By Lütfü SARIBULUT

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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ABSTRACT

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PERFORMANCE ANALYSIS OF UNIFIED POWER FLOW CONTROLLER (UPFC) BY USING DIFFERENT CONTROLLERS

Lütfü SARIBULUT

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
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Nowadays, high voltage transmission networks met enormous power demands are very expensive investments in terms of their costs. Because of this, the importance of effective using the existing transmission lines is increasing. In order to benefit more efficiently from the existing transmission lines, the new methods are being developed and applied by making studies related to this area.

The rapid developments on the area of power electronics have enabled the development of new equipments to be able to benefit more efficiently from the power systems. The equipments based on the power electronics have been improved under the name of Flexible Alternating Current Transmission Systems (FACTS) in the last years. FACTS devices, are quite efficiently at the power control of the transmission lines and increasing their current capacity, and have rapidly developed. FACTS technology has been used extensively at power control, voltage regulation, increasing the transient stability, and decreasing system oscillations. Unified Power Flow Controller (UPFC) is the more efficient among the FACTS equipments which have the potential to increase the power flow and the stability of the transmission line.

In this thesis, the modeling and the developing of UPFC were studied in order to make better the steady state works of the power systems. The effect of UPFC on the power flow of transmission lines were analyzed mathematically and graphically in details. The performances of UPFC were examined by using different controllers.

Keywords: FACTS, UPFC, Power Quality.

ÖZ

YÜKSEK LİSANS TEZİ

FARKLI KONTROLCÜLER KULLANILARAK BİRLEŞİK GÜÇ AKIŞ KONTROLCÜSÜ (UPFC)'nün PERFORMANS ANALİZİ

Lütfü SARIBULUT

ELEKTRİK ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI
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Yüksek gerilim iletim şebekeleri günümüzde büyük güç taleplerini karşılayan maliyetleri bakımından oldukça pahalı yatırımlardır. Dolayısıyla mevcut iletim hatlarının en verimli şekilde kullanılmasının önemi artmaktadır. Bu alanla ilgili çalışmalar yapılarak, mevcut iletim hatlarından daha verimli faydalanmak için yeni yöntemler geliştirilerek uygulanmaktadır.

Güç elektroniği alanındaki hızlı gelişmeler, kullanılan güç sistemlerinden daha verimli yararlanabilmesi için yeni donanımların geliştirilmesine fırsatlar sağlamıştır. Son yıllarda, Esnek Alternatif Akım İletim Sistemleri (FACTS) kapsamında, güç elektroniğe dayalı donanımlar geliştirilmiştir. FACTS cihazları, iletim hatlarının güç kontrolü ve mevcut kapasitesini arttırmada oldukça etkilidir ve hızla gelişmektedir. FACTS teknolojisi güç kontrolünde, voltaj regülasyonunda, geçici kararlılığı arttırmada ve sistem osilasyonlarını azaltmakta yaygın olarak kullanılmaktadır. Birleşik Güç Akış Kontrolcüsü (UPFC), iletim hattının güç akışını ve kararlılığını arttıracak potansiyele sahip olan FACTS aygıtlarından en etkili olanlarından birisidir.

Bu tezde, güç sistemlerinin kalıcı hal çalışmalarının iyileştirilmesi için Birleşik Güç Akış Kontrolcüsü'nün modellenmesi ve geliştirilmesine çalışılmıştır. Birleşik Güç Akış Kontrolcüsü'nün iletim hatlarındaki güç akışı üzerindeki etkisi matematiksel ve grafiksel olarak incelenmiştir. Geliştirilmiş Birleşik Güç Akış Kontrolcüsü modelinde, değişik kontrolcüler kullanılarak performansları karşılaştırılmıştır.

Anahtar Kelimeler: FACTS, UPFC, Güç Kalitesi.

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LIST OF SYMBOLS

V_{pq} : Injected AC voltage by UPFC

θ : Phase angle

I : Line current

V_o : Terminal voltage

ΔV : Injected AC voltage by UPFC in phase with V_o

V_c : Injected AC voltage by UPFC quadrature with the line current I

V_σ : Injected AC voltage by UPFC angular relationship with respect to V_o

I_p : P-axis current component

I_q : Q-axis current component

I_{shp} : D-component of shunt converter current

I_{shq} : Q-component of shunt converter current

V_{dc} : Capacitance voltage

P_{ref} : Reference real power of the line

Q_{ref} : Reference reactive power of the line

P : Real power of the line

Q : Reactive power of the line

V_s : Sending end voltage

V_r : Receiving end voltage

X : Line impedance

L_r : Line inductance

R_r : Line resistance

Vs_{seff} : Sending end voltage effective

P_o : Uncompensated real power

Q_o : Uncompensated reactive power

δ : Transmission angle

ϕ : Angle of injected AC voltage by UPFC

DQ : Synchronously rotating orthogonal system

V_T : Magnitude of the AC side voltage

E_{T1} : Fundamental component of the switched voltage

X_T : The reactance of the shunt converter transformer

I_d^* : Reference current of D component

I_q^* : Reference current of Q component

α : Firing angle

P^* : Order real power

Q^* : Order reactive power

$Vsend_{pu}$: Per unit of sending end voltage

Err : Error

e : Error signal

r : Reference signal

y_m : Output signal

T_I : Integration time constant

T_d : Derivation time constant

V_{PLLa} : A phase pll voltage

V_{Sa} : A phase source voltage

LN : Large negative

MN : Medium negative

SN : Small negative

VS : Very small

SP : Small positive

MP : Medium positive

LP : Large positive

Trapmf : Trapezoidal membership function

Trimf : Triangular membership function

F_i^l : Fuzzy set

c_i^l : Real valued parameter

y^l : System output

c_i^l : Real valued inputs

Fis : Fuzzy inference system

NB : Negative big

NM : Negative medium

NS : Negative small

Z : Zero

PS : Positive small

PM : Positive medium

PB : Positive big

Wtaver : Weighted average

w^l : Overall truth value

$M_{F_i^l}$: Membership function

IVI_{pu} : Amplitude of bus voltage

Gamma : Line angle

RetRon&RetRof: Firing pulses for IGBT

TrgRon&TrgRof: Reference triangular carrier signals

$K_e(t)$: Gain of controller

Rms : Root mean square

LIST OF ABBREVIATION

FACTS	: Flexible Alternating Current Transmission System
EPRI	: Electric Power Research Institute
VSC	: Voltage Sourced Converter
CT	: Current Transformer
OPF	: Optimal Power Flow
DVR	: Dynamic Voltage Restorer
SVC	: Static VAR Compensator
SSSC	: Static Synchronous Series Compensator
IPFC	: Interline Power Flow Controller
TCSC	: Thyristor Controlled Series Capacitor
TCR	: Thyristor Controlled Reactor
TSSC	: Thyristor Switched Series Capacitor
GCSC	: GTO Thyristor - Controlled Series Capacitor
GTO	: Gate Turn-Off
PWM	: Pulse Width Controller
PLL	: Phase Lock Loop
SSG	: Static Synchronous Generator
SVC	: Static VAR Compensator
SVS	: Static VAR System
STATCOM	: Static Synchronous Compensator
TCPST	: Thyristor Controlled Phase Shifting Transformer
UPFC	: Unified Power Flow Controller
SPWM	: Sinusoidal Pulse Width Modulation
P	: Proportional Term
I	: Integral Term
D	: Derivative Term
PI	: Proportional Integral Controller
PID	: Proportional Integral Derivative Controller
FLC	: Fuzzy Logic Controller

FIS : Fuzzy Inference System

IGBT : Insulated Gate Bipolar Transistors

PWM : Pulse Width Modulation

SPWM : Sinusoidal Pulse Width Modulation

FL : Fuzzy Logic

1. INTRODUCTION

1.1 General Outline

In recent years, great electric power demands have been imposed upon high voltage transmission networks in the worldwide. Also, the construction of the new generating units and transmission circuits become more difficult because of economic and environmental reasons. Therefore, power utilities are compelled to benefit from existing generating units, and to bring closer existing transmission lines to their thermal limits. However, the stability of the power system has to be maintained permanent even in the case of contingency conditions, such as loss of transmission lines or generating units, which occur frequently. Hence, the new control strategies are needed to be implemented in order to operate power system effectively without reduction in the system security and quality of supply. In the late 1980s, a new technology program known as Flexible Alternating Current Transmission System (FACTS) was presented by Electric Power Research Institute (EPRI) (Song *et al.*1999). The idea of FACTS technology is to increase controllability and to optimize the utilization of the existing power system capacities using the reliable and high speed power electronic devices instead of mechanical controllers.

FACTS technology opens up new opportunities for controlling the power and enhancing the usable capacity of the present transmission systems. The opportunities arise through the ability of FACTS controllers to control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, phase angle, and damping of oscillations at various frequencies below the rated frequency. These constraints cannot be overcome otherwise, while maintaining the required system stability, by mechanical means without decreasing the transmission capacity. By proving added flexibility, FACTS controllers can enable a line to carry power closer to its thermal rating. Mechanical switching needs to be supplemented by rapid response power electronics.

The development of FACTS devices has followed two technical approaches to target AC transmission problems. One of the technical approaches is thyristor controlled FACTS devices, such as TCR (Thyristor Controlled Reactors), Thyristor Controlled Phase-Shifter. The other technical approach is Voltage Source Converter (VSC) based FACTS devices, such as STATCOM (Static Synchronous Compensator), UPFC (Unified Power Flow Controller) and IPFC (Interline Power Flow Controller). The VSC can generate both inductive and capacitive reactive power. If VSC is coupled with an energy storage device such as dc storage capacitor or battery, it is able to exchange real power with the AC system. If it is operated as a reactive shunt compensator, it is called STATCOM. If it is operated as a reactive series compensator, it is called Static Synchronous Series Compensator (SSSC).

Unified Power Flow Controller (UPFC) is a special arrangement of two VSCs, one of which is connected in series with the AC system and the other is connected in shunt with the AC system with common dc terminal. UPFC is a combination of STATCOM and SSSC, which is coupled via a common DC link. This link allows a bi-directional real power flow between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. The two VSCs, which operate from a common link with a DC storage capacitor, use the technique of power switches. This arrangement functions as an ideal AC to AC power converter in which the real power can freely flow in either direction between the AC terminals of two converters and each converter can independently generate or absorb reactive power at its own AC output terminal. UPFC is able to control concurrently or selectively the transmission line voltage and line impedance, angle or alternatively the real and reactive power flow in the line by means of angularly unconstrained series voltage injection.

The additional storage such as DC capacitor connected to the dc link via an electronic interface would provide the means of further enhancing the effectiveness of UPFC. The controlled exchange of real power with an external source, such as storage is much more effective in control of system dynamics than modulation of the power transfer within a power system. UPFC performs not only the functions of the STATCOM, SSSC and the phase angle regulator but also provides additional flexibility by combining some of the functions of these controllers.

The aim of this research is to examine the performance of different controllers for UPFC by using PSCAD/EMTDC program. In general, the control strategy of UPFC should have preferably the following attributes:

- The steady state objectives (i.e. real and reactive power flows) should be readily achievable by setting the references of the controllers.
- The dynamic and transient stability improvement by using appropriate controller references.

To simplify the design procedure, we carry out the design for the series and the shunt branches separately. The design has to be validated when the various subsystems are integrated. The design tasks are given in the following.

- *Series voltage control*: The power flow will be controlled by using the series voltage injection.
- *Shunt voltage control*: The controlling of the sending end bus voltage and the regulating of the DC side capacitor voltage will be controlled by using the reactive.

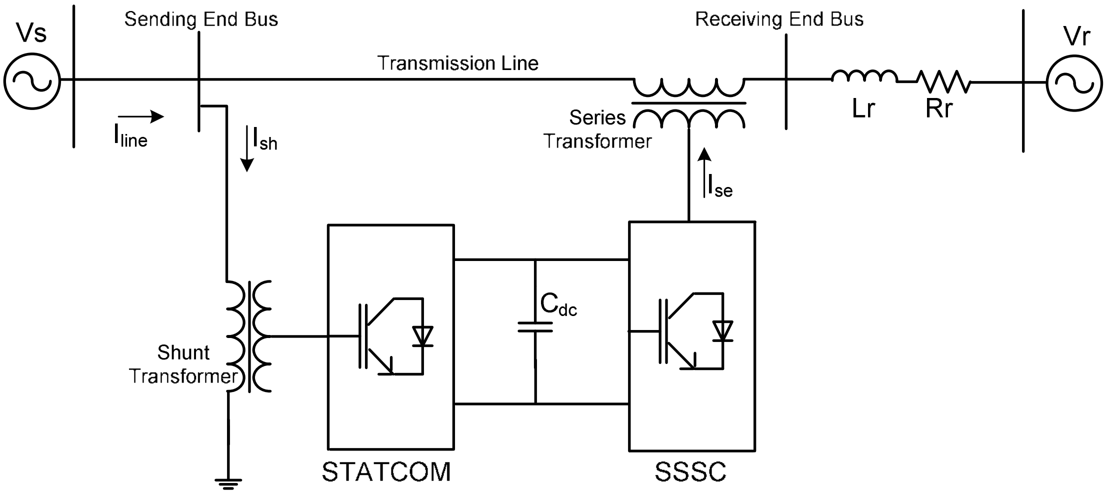


Figure 1. 1 The test system used in this thesis

The report of the work done is organized as follows:

After this introductory chapter, the literature surveys associated with UPFC are given in chapter 2.

The chapter 3 gives a brief overview of the FACTS devices. The general definition and operation of FACTS devices, basic control functions and characteristics of UPFC are given in this chapter.

The chapter 4 discusses the proposed control strategy and the developed controllers. The power flow in the line is clarified as mathematical equations, and the effects of UPFC are mentioned on power flow. The general controllers (P, PI and PID) are explained and developed fuzzy controller is examined.

The chapter 5 presents the actualizing the proposed UPFC model and its controllers in simulink part by using PSCAD/EMTDC program.

The chapter 6 discusses the simulation results on the test system for different cases.

The chapter 7 presents the conclusions. Adequate references are provided at the end of this chapter.

1.2 Conclusion

The general outlines of FACTS devices are discussed in this chapter. The outline of UPFC and the organization of thesis are given.

2. LITERATURE SURVEY

In this chapter a literature survey of UPFC operation, modeling and control will be studied.

UPFC is the most versatile and complex electronic power equipment that has emerged for the control and the optimization of power flow in electrical power transmission systems. Until UPFC was introduced, the parameters that affect the real and the reactive power flows in the line (i.e. the line impedance, voltage magnitudes at the terminals of the line or phase angle) were controlled separately by using either mechanical or other FACTS devices such as Static VAR Compensator (SVC), Thyristor Controlled Reactor (TCR) etc. UPFC was devised for the real time control and the dynamic compensation of AC transmission systems by providing multifunctional flexibility required solving many of the problems faced in the delivery industry. However, UPFC is able to control simultaneously or selectively all parameters affecting the power flow in the transmission line (i.e., voltage, impedance and phase angle). Also, UPFC can be used for voltage support, transient stability improvement and the damping of low frequency power system oscillations. The modeling and the controlling of UPFC have come into intensive investigation in the recent years due to its attractive features. The UPFC, which was proposed by L. Gyugyi in 1992 (Gyugyi *et al.*, 1992) is one of the most complex FACTS devices in a power system today. Several references in technical literature can be found on development of UPFC steady state, dynamic and linearized models.

2.1 UPFC Applications

A Newton-Rhapson method is used in references (Fuerte *et al.*, 1997; Ambriz *et al.*, 1998). In (Fuerte *et al.*, 1997), this algorithm was improved for UPFC application. It permits instantaneous or independent control of power flow and voltage magnitude. In (Ambriz *et al.*, 1998), Newton-Rhapson algorithm based Nabavi-Niaki and lravani model has been implemented in UPFC-OPF model. This algorithm is very complex and hard to apply. Also, it is quite sensitive to initial condition settings. The order of the Jacobian matrix is increased significantly in the iterative procedure. The selection of suitable initial conditions can solve the oscillations of power system dynamics.

In references (Lo K.L *et al.*, 1998; Nabavi-Niaki *et al.*, 1996; Xu *et al.*, 2004), the steady state model, which is necessary for the analysis of the power flow operation of device embedded in a power system, is preferred. In (Lo K.L *et al.*, 1998), Ann based direct control algorithm method is used to compare the simulation results with steady state model. UPFC is modeled as a voltage source in series with line reactance, and the mathematical calculation is incorporated with Jacobian Matrix. The model is simple and helpful at understanding the impact of UPFC in the power system. However, the amplitude modulation and phase angle control signals of the series VSC have to be adjusted manually in order to find the desired load flow solution.

In reference (Papic *et al.*, 1997), the basic control method is used. It consists of two control mechanism. One of them is real and reactive power flow control mechanism and the other is sending end bus voltage and DC voltage magnitude control mechanism. The vector-control approach is one of the most used control scheme. It is proposed by Schauder and Metha in 1993 (Schauder *et al.*, 1993). The decoupled control of the real and the reactive powers can be applied easily in this method and it is suitable for UPFC application. The decoupled control can be achieved in this scheme by changing the three-phase balanced system into a synchronously rotating orthogonal system (DQ transform). The D-axis of synchronously rotating orthogonal system corresponds with the instantaneous voltage vector and the Q-axis is orthogonal to it. The D-axis current component coincides with the instantaneous real power and the Q-axis current coincides with the reactive power in this coordinate system. This control scheme can be applied both for series and shunt converters control in references (Yonggao *et al.*; 2005, Qing *et al.*, 1996; Fujita *et al.*, 2006). Proportional-Integral (PI) controller is used to get dynamic values close to their reference values. The sending end bus voltage magnitude and the dc link voltage are measured to take reference values for components of system current in references (Schauder *et al.*, 1993; Yonggao *et al.* 2005; Padiyar *et al.*1998; Liu *et al.*2005). This control method is simple and easy to implement.

Another approach is automatic power flow method (Kannan *et al.*2004). The synchronously-rotating orthogonal system method is used in this method in the same way as basic control method. There are some differences between the basic control method and the automatic power flow method. In the basic control method, shunt and series converters of current decompose into two components while in the automatic power flow, the sending and the receiving buses voltage decompose into two components. The sending end voltage and the dc capacitor voltage are measured to take reference value of shunt converter, and the line real and reactive powers are measured to take references of series converter (Kannan *et al.*2004; Hosseini *et al.* 2004; Zhu *et al.* 2005; Aihong *et al.* 2005). In order to get the desired result, the reference value of system dynamics must be pre-specified (i.e. reference real and reactive power value, dc capacitance reference value... etc).

The dynamic model of UPFC can be found in references (Uzunovic *et al.* 1999; Sen *et al.* 1998; Zhou *et al.* 2004; Nguyen *et al.* 2004). Two voltage sources are used in this model. One of the voltage sources is connected in series and the other is connected in shunt with the power network to represent the series and shunt VSCs. Both voltage sources are modeled to inject voltages to power system with respect to required power for the system and the voltage sources. In reference (Kalyani *et al.* 2003), the DC link capacitor and the sending end dynamics are used by shunt voltage source to regulate the dc link voltage and the sending end bus voltage. In reference (Nguyen *et al.* 2004), the dynamic model is used for Dynamic Voltage Restorer (DVR). One of the dynamic models of references (Kannan *et al.*2004; Kalyani *et al.* 2003; Nguyen *et al.* 2004) will be used in this thesis.

The linearized model of UPFC applications is practical for small signal analysis and damping controller design. The linearized model of UPFC can be found in references (Wang *et al.*1999; Smith *et al.* 1997). In reference (Wang *et al.*1999) the DC link dynamics do not contain, and in reference (Smith *et al.* 1997) the sending and receiving buses of UPFC are also assumed as generator terminal buses when the model derived.

Other control methods are current injection method, Hysteresis control method and the non-linear control method. Some of the FACTS devices have been designed by using some of these techniques as UPFC in reference (Son et al 2004; Meng *et al.* 2000; Sutanto *et al.* 2000; Green *et al.* 1989; Lu *et al.* 1997).

As another approach, fuzzy controller and Neural-Network based controller are used with several control methods in UPFC (Eldamaty *et al.* 2005; Orizondo *et al.* 2006; Ma *et al***.** 2000; Venayagamoorthy *et al.* 2005; Mishra *et al.* 2006). The fuzzy controller is attractive for several control method, because it does not require the mathematical model of the system under study conditions. It can cover wider range of operating conditions, and is simple to implement. The fuzzy models are created by using Sugeno Inference System and used in the series control mechanism of UPFC in this thesis (Eldamaty *et al.* 2005). Fuzzy is used in the power frequency model of UPFC in reference (Mok *et al.* 2000). PI and fuzzy controller are used together in the current injection model in references (Orizondo *et al.* 2006; Ma *et al.* 2000). Likewise, the fuzzy controller will be used with the PI controller in this thesis.

The objective of this thesis is to develop a UPFC model by using PSCAD/EMTDC program, to design its controls mechanism with several controllers, and to make performance analysis of these controllers.

2.2 Conclusion

The basic operation modes of shunt and series parts are given in this chapter. In the next subsection, the application of UPFC is explained by classified according to control methods.

3. FLEXIBLE AC TRANSMISSION SYSTEM

3.1 Introduction to FACTS

FACTS technology is used extensively to enhance the controllability and the capability of power transfer in the AC systems. FACTS involve conversion or switching power electronics wide-range megawatts relatively.

The power electronics and the switching technology have been rapidly growing area for a wide range of needs at the end-user side in two decades. The electricity is an incredible form of energy that can be converted to many different forms of energy, and it is used to bring new technologies for the humans. The power conditioning technology is used by customers under the term of power quality when the custom power technology was complemented.

Nowadays, large power demands have been provided on the transmission network, and these demands will continue to rise because of the increasing number of factories and the high competition among utilities. The increased demands on the transmissions, the absence of the long term planning, and the need to provide the open access to generating companies and the customers have created the tendencies toward less security, and reduced the quality of the supply. FACTS technology is essential to alleviate some problems, but not all of them. It enables utilities to get more services from the transmission facilities and to enhance the power system reliability.

FACTS technology offers new opportunities to control the power and to enhance the utility of present network and the systems, as well as new and upgraded lines. The established system can be controlled at reasonable cost by increasing the capacity of transmission lines.

FACTS devices give facilities to the controllers that are able to control the interrelated parameters, which govern the operation of transmission systems including series and shunt impedance, current, voltage, phase angle and the damping oscillations at various frequencies below the rated frequency. These constraints cannot be overcome while the required system reliability is maintained by mechanical means without lowering the usable transmission capacity. By providing added flexibility, FACTS devices are able to carry the line power to nominal ratings. It must be emphasized that FACTS is an applicable technology to implement in the companies and industries.

Some of the power electronic controllers are introduced to the technical community by Narian G. Hingorani (Hingorani *et al.* 1993) before introducing FACTS concept. However, the unique aspect of FACTS technology is that this umbrella concept reveals the large potential opportunity for the power electronics technology to enhance the value of power system ratings.

3.2 FACTS Controllers

In general, FACTS devices can be divided into four categories.

- Series controllers
- Shunt controllers
- Combined series-series controllers
- Combined series-shunt controllers

3.2.1 Series Controllers

The control concept of series compensators is related to how the maximal power is transmitted in the line and the steady state power transmission is attainable. These are related to the voltage stability and the power oscillation damping. The series controllers inject the voltage in series with the line. The reactive power is supplied or consumed by series controller only as long as the voltage is quadrature with the line current. Also, other different phases will involve the utilization of the real power as well. The some of series controllers are listed below.

- *Thyristor Controlled Series Capacitor (TCSC)*
- *Thyristor Switched Series Capacitor (TSSC)*
- *GTO Thyristor-Controlled Series Capacitor (GCSC)*

- *Static Synchronous Series Compensators (SSSC):* The VSC based series compensator is known as Static Synchronous Series Compensator (SSSC). It was proposed by Gyugyi in 1989. SSSC represents an alternative like synchronous voltage source in the series line compensation. It is operated as series compensator without an external electric energy source, and its output voltage is controllable and is in quadrature with the line current. It is implemented by thyristor-based VSC and used to provide the controllable series compensation, seen in Figure 3.1. When SSSC is operated with an appropriate dc power supply at its input terminals, this compensator is used in generators and solid-state switching converters. When SSSC is coupled with an energy storage capacitor, it can be used only to generate or absorb the reactive power from the system. The SSSC is connected to the three-phase transmission line with series VSC through a coupling transformer.

The power flow can be increased in the line by inserting an additional series capacitive reactance. As a result of this, the effective line impedance is decreased. The power flow can be also decreased by inserting an additional inductive reactance. Consequently, the effective reactance is increased. It is employed to increase or to decrease the overall reactive voltage drop across the line. Thus, it is modeled as an inductive or a capacitive reactance in series with the transmission line. This variable reactance influences the power flow in the transmission line. The voltage, which is in phase with the line current, meets the losses in the converter.

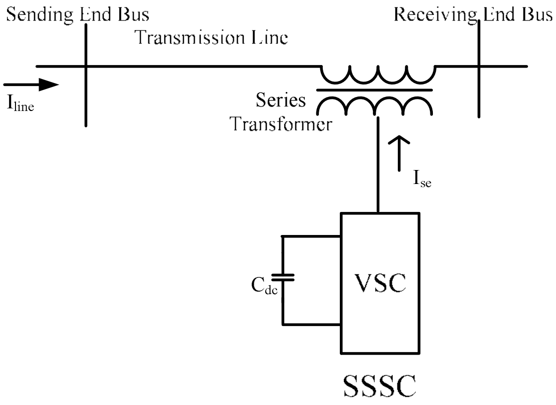


Figure 3. 1 Basic scheme of SSSC

The battery storage or capacitance can also be connected with the series controller to inject the series voltage with variable angle in the line. Without an extra energy source, SSSC can inject only variable voltage, which is 90^o leading or lagging the current.

3.2.2 Shunt Controllers

The shunt controllers may be seen as variable impedance, variable source, or a combination of these variables. The main operation principle of shunt controllers is to inject the current to the line from the connection point of the system. The shunt controller supplies or consumes only variable reactive power when the injected current is in quadrature with the line voltage. The shunt controller supplies or consumes real power when there is any other phase relationship with the line voltage. The some of shunt controllers are listed below.

- *Static Synchronous Generator (SSG)*
- *Static VAR Compensator (SVC)*
- *Thyristor Controlled Reactor (TCR)*
- *Static Synchronous Compensator (STATCOM):* A static synchronous compensator (STATCOM) is a shunt-connected reactive power compensation device that is capable of generating or absorbing reactive power whose output can be varied to control specific parameters of an electric power system. In general, it is a solid-state switching converter, capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy. Storage device is coupled at STATCOM input terminals.

STATCOM system is comprised of three main parts: a voltage source converter, a coupling reactor or a step-up transformer, and a controller. The STATCOM is connected to the power networks at a point of common coupling. All required voltages and currents are measured and fed into the controller in order to be compared with the references. The feedback control is used as outputs by switching signals to drive the main semiconductor switches of the power converter accordingly. The magnitude and phase of the VSC output voltage is controlled by the turn-on/turn-off of semiconductor switches in the VSC.

Figure 3.2 shows a simple Figure of STATCOM based on a VSC. The reactive power exchange between the converter and the AC system can be controlled by varying the amplitude of the three-phase output voltage of the converter. That is, if the amplitude of the output voltage is increased above that of the utility bus voltage, then the current flows through the reactance from the converter to the AC system and the converter generates capacitive reactive power for the AC system. If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the AC system to the converter, and the converter absorbs inductive reactive power from the AC system. If the output voltage is equal to the AC system voltage, the reactive power exchange is zero.

Similarly, the real power exchange between the converter and the AC system can be controlled by adjusting the phase shift between the converter output voltage and the AC system voltage. That is, the converter can supply real power to the AC system from its dc energy storage if the converter output voltage is made to lead the AC system voltage. On the other hand, it can absorb real power from the AC system for dc energy if its voltage lags the AC system voltage.

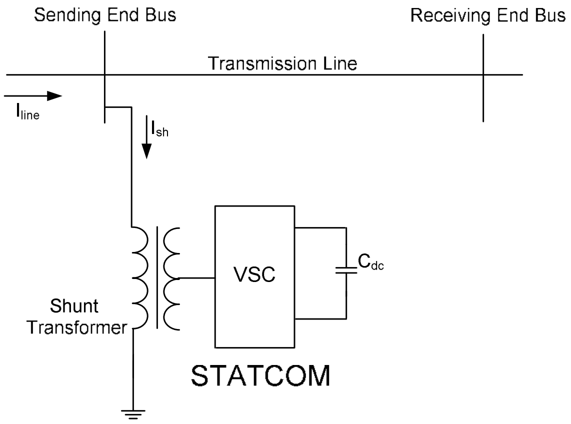


Figure 3. 2 Basic scheme of STATCOM

Although reactive power is internally generated by the action of converter switches, it is still necessary to have a dc capacitor connected across the input terminals of the converter. The need for the capacitor is primarily to provide a circulating current path as well as a voltage source. The magnitude of the capacitor is not important, but generally it is chosen such that the dc voltage across its terminals remains fairly constant so that it doesn't contribute to the ripples in the dc current. This results in slight fluctuations in the output power of the converter.

3.2.3 Combined Series-Series Controllers

These controllers are combined with separate series controllers. They are used in the multi-line transmission system and operated in a coordinated manner in the line. The series-series controllers provide independent series reactive compensation for each line, but also transfer the real power among these lines. One of the series-series controllers is Interline Power Flow Controller (IPFC). It is used to balance both real and reactive power flow in the lines and thereby the maximum utilization of the transmission system is supplied.

3.2.4 Combined Series-Shunt Controllers

The structure of series-shunt controllers are combined with series and shunt controllers. They are used in the multi-line transmission system and operated in a coordinated manner in the line. Some of the series-shunt controllers are given in the following:

- *Thyristor Controlled Phase Shifting Transformer (TCPST)*
- *Unified Power Flow Controller (UPFC)*

3.3 Unified Power Flow Controller (UPFC)

Gyugyi proposed UPFC concept in 1991(Gyugyi *et al.* 1992). The UPFC was devised for the real time control and the dynamic compensation of AC transmission systems, providing the required multifunctional flexibility in order to solve many of the problems facing the delivery industry. Within the framework of traditional power transmission concepts, UPFC is able to control simultaneously or selectively all the parameters affecting the power flow in the transmission line (i.e., voltage, impedance and phase angle) and this unique capability is signified by the adjective *unified* in its name. The UPFC is a combination of STATCOM and a SSSC, which are coupled via a common DC link. This link allows a bi-directional flow of real power flow between the shunt output terminals of the STATCOM and the series input terminals of the SSSC. This real power is controlled to provide concurrent real and reactive series compensation without an external electric energy source. The active power for the series converter is obtained from the line via the shunt converter STATCOM. It is also used for voltage phase and amplitude to control its reactive power. This is a complete controller for controlling the active and reactive power through the line, as well as line voltage controller. The details circuit of UPFC is shown in Figure 3.3. Additional storage, such as capacitor or DC voltage source connected to the dc link via an electronic interface, would provide the means of enhancing the effectiveness of UPFC.

3.3.1 Circuit Arrangement

The general definition of UPFC is combined with two converters and they are considered as a VSC in the applications. The Gate Turn-Off (GTO) thyristor valves are used in the VSC, as illustrated in the Figure 3.3. They are labeled as Converter A and Converter B and coupled back to back a common dc link provided by a dc storage capacitor. This arrangement functions as an AC to AC power converter. The real power can flow bi-directionally between the AC terminals of the converters, and each converter can generate or absorb independently reactive power at its AC output terminal.

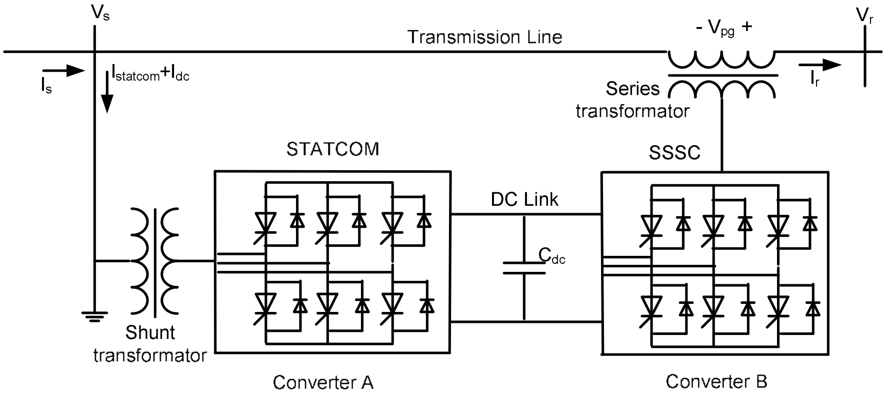


Figure 3. 3 Basic circuit of UPFC

3.3.2 Operation Principle of UPFC

The AC voltage V_{pq} is provided by converter B, and it is the main function of UPFC. The voltage V_{pq} is injected with controllable magnitude V_{pq} ($0 \leq V_{pq} \leq V_{pqmax}$) and phase angle θ ($0 \leq \theta \leq 360$) at the power frequency. It is in series with the line via an insertion transformer. The injected voltage is thought as a synchronous voltage source. The transmission line current flows through the output terminal of series VSC insertion transformer and the power exchange with the AC system is bring about in output terminal of series VSC insertion transformer. The real power is exchanged at the AC terminal of shunt converter and is converted as required dc power. It appears as positive or negative real power demanded by the dc link. The reactive power exchanged at the AC terminal is generated internally by the converter.

The converter A is to supply or absorb the real power from the system for requirements of the converter B and the common dc link. Also, the converter A can generate or absorb reactive power from the system according to bus voltage which converter is connected to the system. Thus, when the reactive compensation is required, it can provide to the system independently. There is a closed path for the real power flow from the converter B during the series voltage injection to the line. The required real and reactive power of the system is supplied or absorbed by the converter B. Thus, the converter A can operate reactive power exchange with the line independent from the reactive power exchange of the converter B. This means that there is no continuous reactive power flow through the DC link in UPFC.

3.3.3 Control Functions of UPFC

The operation of UPFC depends on reactive shunt compensation, series compensation and phase shifting. These functions and multiple control objectives can be supplied by UPFC with by adding the injected voltage V_{pq} (with appropriate amplitude and phase angle, to add the terminal voltage V_o). Using the phasor representation, the basic UPFC power flow control functions are illustrated in Figure 3.4.

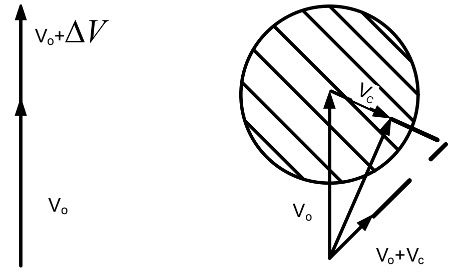
- *Terminal voltage regulation*: It is shown in Figure 3.4 at (a).It is similar with a transformer tap-changer.

Where V_o is the line voltage and ΔV (V_{pq}) is injected in-phase (or anti-phase) with V_o.

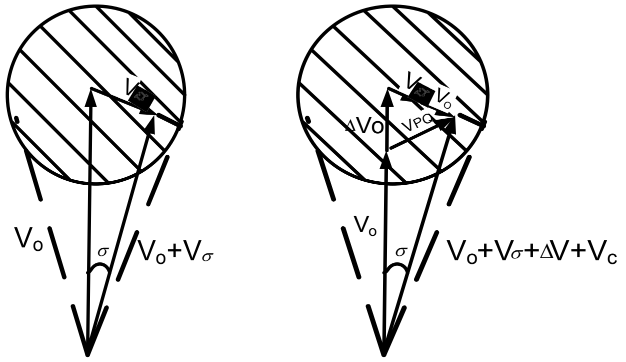
- *Series capacitor compensation*: It is shown in Figure 3.4 at (b). V_c (V_{pq}) is in quadrature with the line current I.
- *Transmission angle regulation (phase shifting):* It is shown in Figure 3.4 at (c). V_σ (V_{pq}) is injected to V_o according to angular relationship with V_o. Therefore, the desired phase shift (advance or retard) achieves without any change in magnitude.
- *Multifunctional power flow control*: It is shown in Figure 3.4 at (d) where $V_{pq}=\Delta V + V_\sigma + V_o$. It is accomplished by instantaneous terminal voltage regulation, series capacitive compensation, and phase shifting.

With suitable electronic controls, UPFC can cause the series-injected voltage vector to vary rapidly and continuously in magnitude or angle as desired. The control of UPFC is based upon the vector-control approach proposed by Schauder and Mehta for advanced static VAR compensators (i.e., for STATCOM) in 1991.

The symbols *V* and *I* are used as voltage and current vectors. These vectors are not stationary. According to the changing of the phase values, it moves around a fixed point in the plane. It describes various trajectories which become circles. For the purpose of power control, it is useful to view these vectors in an orthogonal coordinate system with D and Q axes such that the D axis is always coincident with the instantaneous voltage vector V, and the Q axis is in quadrature with it. In this coordinate system, the D-axis current component i_d accounts for the instantaneous real power, and Q-axis current component i_q for reactive power. Under balanced steady state condition, the D-axis and Q-axis components of the voltage and current vector are constant quantities. In this thesis, D-axis and Q-axis components of the voltage will be used in the control mechanism of series converter.



(a) Voltage Regulation b) Series Compensation



(c) Phase Angle Regulation (d) Multi-Function

Figure 3. 4 Basic UPFC control functions

Operation modes of UPFC are classified in two groups. One of these groups is for shunt converter and the other is for series converter. These modes are given in the following.

3.3.4 Shunt Converter

The operation principle of shunt converter is used to draw a controlled current from the line. This current is created by calculating both the requirement of the real power for the series converter and the reactive power to set its quantity for any desired reference level (inductive or capacitive) within the capability of the converter. Reactive compensation control mode of shunt converter is very similar to those commonly employed on conventional SVCs.

- *VAR Control Method:* According to the system situation, the reference input signal is an inductive or capacitive VAR request. The controller takes the reactive reference to translate into a corresponding shunt current request and adjusts the gating of the converter to establish the desired current. A feedback signal representing the dc bus voltage and the current feedback signals is taken by the controller obtained from current transformers (CTs) and V_{dc} is also required.

- *Automatic Voltage Control Mode*. The shunt reactive current of converter is automatically regulated to keep the transmission line voltage at the point of shunt converter connected to a reference value.

3.3.5 Series Converter

The series converter injects the voltage series with the line to control the magnitude and angle of the line voltage. The purpose of voltage injection is always affecting the direction of power flow in the line. The real value of injected voltage can be determined in different ways in the following.

- *Direct Voltage Injection Model.* According to the reference input, the converter simply generates a voltage vector at required magnitude and phase angle. A special situation of the model is that when the injected voltage is kept in quadrature with the line current, only the reactive series compensation is provided.
- *Phase Angle Shifter Emulation Model*: The voltage is injected at the amount of the angle which is specified by the reference input so that the phase angle of line voltage is shifted simply.
- *Line Impedance Emulation.* The voltage is injected proportion with the line current by series converter. Thus, the series transformer is seen as impedance when viewed from the line. The reference input is selected by desired impedance and in general it may be complex impedance with resistive and reactive components of either polarity. There must be taken care in this mode to avoid values of negative resistance or capacitive reactance because of resonance or instability situation.
- *Automatic Power Flow Control Mode*. In this control mode, the vector control system determines the voltage injected as series automatically and continuously by a vector control system to ensure that the desired real power (P) and reactive power (Q) are maintained despite system changes. Also, this mode can be used dynamically for system oscillation damping.

3.3.6 Power Flow Control with UPFC

The performance of UPFC is demonstrated on the real and reactive power flow by keeping the sending end and receiving end bus voltages constant (at 1.0 per unit (pu) magnitude, and a fixed phase angle). The automatic power flow control mode is preferred when the real and reactive power of line is kept at given reference values. The important point is that the power flow should be changed much more gradually and carefully in the real system in order to avoid possible dynamic disturbances in the system.

3.3.7 Operation under Line Faults

According to the location of the system fault, the line current can reach at maximum ratings or exceed the converter rating during faults. The current of the compensated line flows through the series converter of UPFC. When the fault condition is sensed by the series controller of UPFC, it enters the bypass-operating mode immediately. In this mode, the value of the injected voltage and the line current would be reduced to zero. The series converter would be bypassed by the series converter valve, reconfigured electronically for terminal shorting or through a separate high current thyristor valve. After fault condition is cleared by series control mechanism, the mechanical bypass breaker would also be employed normally.

3.4 Conclusion

In this chapter, basic concepts of FACT devices are given. These devices are divided in four groups and these groups are explained with given examples. STATCOM and SSSC, two parts of UPFC are studied in this chapter. Later, basic concepts of UPFC are given in terms of its circuit arrangement, operation principles, basic control functions and structure. The behavior of UPFC facing faults in the system is mentioned in this chapter.

4. CONTROLLERS FOR UPFC

4.1 Basic Concepts

UPFC is combined with STATCOM and SSSC. These parts are coupled together with common DC link (capacitor) to allow the real power flow between the series and shunt converter output terminals bi-directionally, and to provide real and reactive line compensation without an external energy source. UPFC is able to control the series voltage injection ($\Delta V\lfloor\underline{\theta}$) by the means of unconstrained angle. The transmission line with UPFC, which is extended in AC transmission network, is shown in the Figure 4.1.

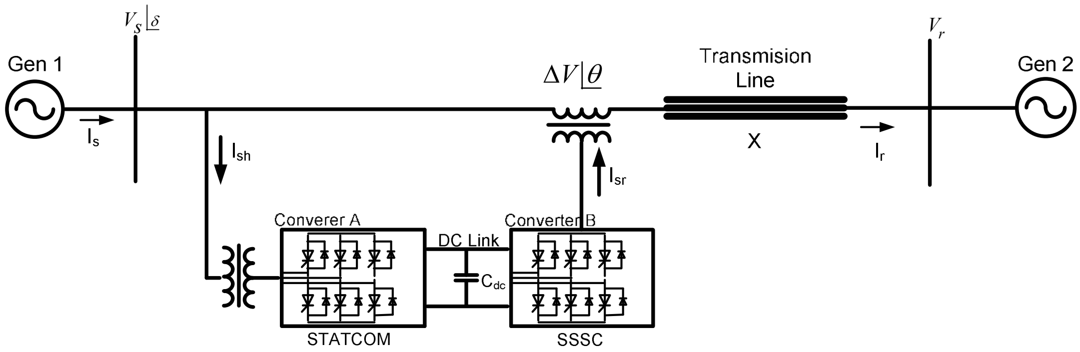


Figure 4. 1 AC Transmission network with UPFC

The voltage represented by a phasor $\Delta V\lfloor\underline{\phi}$ is injected by SSSC in series with the transmission line. The magnitude of ΔV is limited from 0 to 0.5 pu and its angle ϕ is constrained from 0° to 360° (Song *et al.*1999). This voltage can be added vectorally to the sending end voltage ($Vs\lfloor\underline{\delta}$), and the transmission line voltage can be seen as $Vs+\Delta V\lfloor\underline{\phi}$, as shown by the Figure 4.1. Thus, the sending end voltage (V_{ef}) is effectively on the line voltage. According to this situation, UPFC affects both the magnitude and the phase angle of the line voltage on the transmission line. Hence, it is reasonable to expect its ability to control the transmittable real and reactive power demand by varying the magnitude and phase angle of the line at any given transmission phase angle between the sending and receiving end voltages.

The transmitted real (P_o) and reactive power (Q_o) of the transmission above without UPFC (from sending to receiving end bus) are given by the expression.

$$P_o(\delta) = \frac{V_s V_r \sin(\delta)}{X} \tag{4.1}$$

$$Q_o(\delta) = \frac{V_r (V_s \cos(\delta) - V_r)}{X} \tag{4.2}$$

The real and reactive power flow of the transmission line at the receiving end with UPFC is given by following equations (4.1) and (4.2).

Real power of the system with UPFC:

$$P(\delta, \phi) = \frac{V_s V_r \sin(\delta) + \Delta V V_r \sin(\phi)}{X} \tag{4.3}$$

From equation (4.1) and (4.3)

$$P(\delta, \phi) = P_o(\delta) + \frac{\Delta V V_r \sin(\phi)}{X} \tag{4.4}$$

$$\Delta V \sin(\phi) = \frac{P(\delta,\phi) - P_o(\delta) X}{V_r} \tag{4.5}$$

Reactive power of the system with UPFC:

$$Q(\delta, \phi) = \frac{V_r (V_s \cos(\delta) + \Delta V \cos(\phi) - V_r)}{X} \tag{4.6}$$

From equation (4.2) and (4.6)

$$Q(\delta, \phi) = Q(\delta, \phi) = Q_o(\delta) + \frac{V_r \Delta V \cos(\phi)}{X} \tag{4.7}$$

$$\Delta V \cos(\phi) = (Q(\delta, \phi) - Q_o) \frac{X}{Vr} \tag{4.8}$$

To provide the required real and reactive power, the magnitude and phase angle of the series-injected voltage from equation (4.5) and (4.8) are given by following equations:

$$\Delta V = \frac{X}{Vr} \sqrt{(P(\delta,\phi) - P_o)^2 + (Q(\delta,\phi) - Q_o)^2} \tag{4.9}$$

Phase angle of injected voltage,

$$\phi = a\tan\left(\frac{P(\delta,\phi) - P_o}{Q(\delta,\phi) - Q_o}\right) \tag{4.10}$$

The equations (4.9) and (4.10) give information about ΔV and the phase angle ϕ of series-injected voltage to get the demanded real and reactive power by the system within the specified range defined by the maximum limit of injected ΔV . The phasor diagram based on the mathematical derivation above, which gives the magnitude and phase angle of injected voltage to meet the demand of real and reactive power of the system, is obtained, as shown in Figure 4.2 (Song *et al.* 1999).

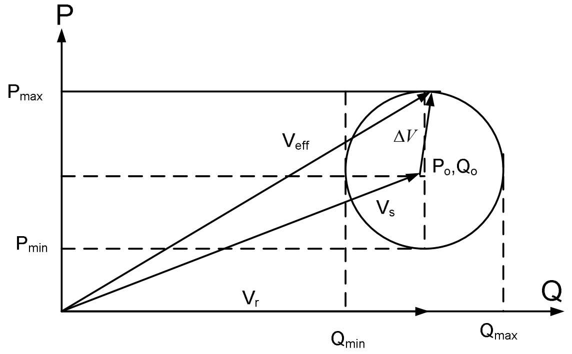


Figure 4. 2 The transmittable power versus phase angle (δ) of UPFC

The transmittable of the real and reactive power will be specified by the maximum limit of injected ΔV .The wide range of controlling the transmitted power independent from the transmission angle (δ) indicates not only superior capability of UPFC in power flow applications, but also promises powerful capacity for transient stability improvement and power oscillation damping. The controllable of the real power (P) and the reactive power (Q) at the receiving end between any transmission angle (δ) can be seen in the following mathematical equations.

$$P_o(\delta) - \frac{\Delta V_{\max}}{X} \le P(\delta,\phi) \le P_o(\delta) + \frac{\Delta V_{\max}}{X} \tag{4.11}$$

$$Q_o(\delta) - \frac{\Delta V_{\max}}{X} \le Q(\delta,\phi) \le Q_o(\delta) + \frac{\Delta V_{\max}}{X} \tag{4.12}$$

The powerful capabilities of UPFC are discussed above in terms of conventional transmission control concepts. It can be integrated into a generalized power flow controller that is able to maintain prescribed controllable real power and reactive power Q in the line (Song *et al.* 1999)

4.2 Controlling the Real and Reactive Power Flow

Considering the equations (4.9) and (4.10), the real and reactive power change from the uncompensated values $P_o(\delta)$ and $Q_o(\delta)$ as a function of the magnitude and the phase angle of the injected voltage ΔV. As the angle ϕ is an unrestricted variable $0^0 < \phi < 360^0$, the attainable boundary of the control region for $P(\delta,\phi)$ and $Q(\delta,\phi)$ is obtained from a complete rotation of the phasor ΔV with its maximum $\Delta V_{\max}$.

The equations mentioned above verify that this control region is a circle with a center defined by the coordinates defined by $P_o(\delta)$ and $Q_o(\delta)$, and the radius is given by following equation:

$$(P(\delta,\phi)-P_O(\delta))^2+(Q(\delta,\phi)-Q_O(\delta))^2=(\frac{\Delta V}{X})^2 \qquad (4.13)$$

The circular control regions are defined by the equation (4.13). These regions are shown in the Figure 4.3 and 4.4. The center of these circuses are $P_o(\delta)$ and $Q_o(\delta)$ at angles $\delta=0°$, $\delta=30°$, $\delta=60°$ and $\delta=90°$ respectively. The focus of the centers are indicated by the + sign as δ varies between $0°$ and $90°$.

When the transmission line angle (δ) and amplitude ΔV are zero, the real power $P_o(\delta)$ and reactive power $Q_o(\delta)$ flows are zero. According to this situation, the system is at standstill at the origin of the P and Q coordinates. It is illustrated as a case in the Figure 4.3. The circle around the origin of the plane is the locus of the corresponding Q and P values (at receiving end). It is obtained as the voltage phasor ΔV which is rotated around itself by a full revolution ($0^0 < \phi < 360^0$) with its maximum value $\Delta V_{\max}$.The boundary of the circle in the (P, Q) plane shows all P and Q values obtainable with UPFC in accordance with given rating. The UPFC with the specific voltage rating of 0.5 pu is able to obtain 0.5 pu power flowing into either direction without imposing any additional reactive power demanded on either the sending or the receiving end bus, as seen from Figure 4.3 and 4.4.

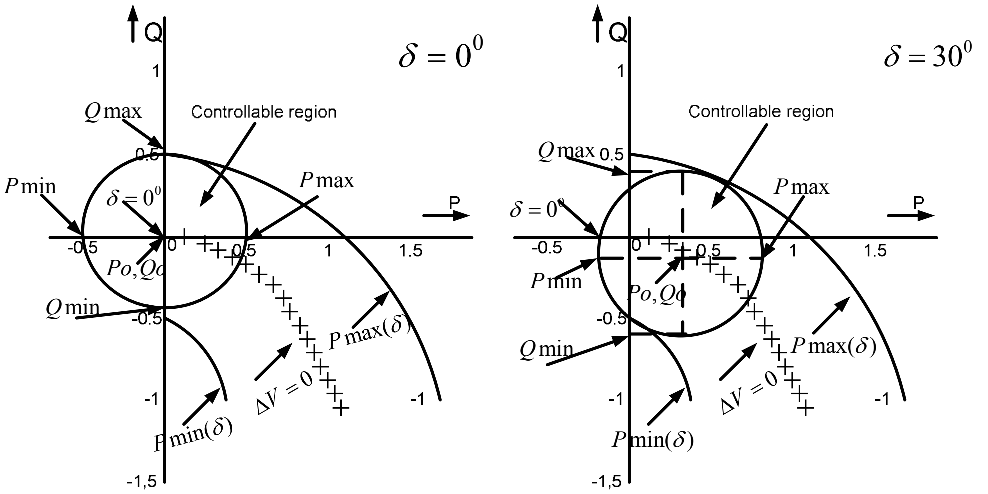


Figure 4. 3 Control region of line power with a UPFC for δ=0° and $\delta = 30°$

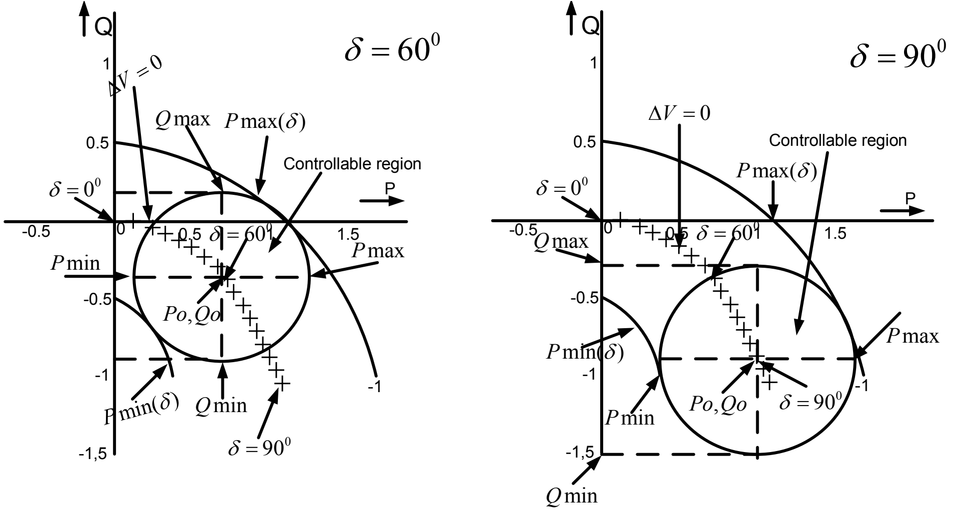


Figure 4. 4 Control region of line power with UPFC for $\delta = 60°$ and $\delta = 90°$

The skills of UPFC demonstrated in the Figures 4.3 and 4.4 shows the capability of controlling the real and reactive power flow independently at any transmission angle provide a powerful tool for AC transmission control.

4.3 Control Methods Used in Shunt and Series Converter

The control methods of these converters are studied individually by taking into account that UPFC is a combination of shunt and series converters which are coupled via a common DC link (capacitor). The operating characteristics of UPFC exhibit excellent performance because of its unique ability to inject an AC compensating voltage vector $\Delta V\lfloor\phi$ with arbitrary magnitude and angle in series with the transmission line within specified equipment's maximum rating limits. Several control methods are discussed in chapter 2. The basic control, automatic control and dynamic control methods based on three-phase balanced system into a synchronously rotating orthogonal system (DQ transform) are used most commonly in the control mechanism of UPFC. A dynamic control method is studied for each converter individually in this thesis. The structures of converters used in shunt and series parts of UPFC are examined in detail Appendix A. The DQ transform is discussed with details at Appendix B.

4.3.1 Control Method of Shunt Converter

The shunt converter operates to draw a controlled current from the transmission line for the following reasons;

- To keep the transmission line voltage at its reference value at the connection point of the line by providing or absorbing reactive power.
- To maintain capacitance voltage level at its reference value on the DC link.

Before understanding the control mechanism of shunt converter, it is assumed that there is no real power exchanged within the system in the steady state. Hence, the DC source can be replaced by a capacitor. The real power is required to compensate capacitor voltage. The energy requirement of this capacitor is very small and this required instantaneous real power is provided by STATCOM in perfectly balanced conditions. Therefore, the role of the capacitor is to provide energy storage during transients, unbalanced operation and also to provide the reactive power to keep the transmission line voltage at its reference value. The mathematical equation of the reactive current entering the shunt converter is given as follow:

$$I_{shq} = \left(\frac{(V_s - V_{sh})}{jX_{sh}}\right) \tag{4.14}$$

The magnitude of the AC side voltage is V_s, the fundamental component of the switched voltage which is directly proportional to the DC bus voltage on the valve side of the transformer is V_{sh} and the reactance of the shunt converter transformer is X_{sh}. The circuit is transformed to the AC network side. Thus, the turn ratio of transformer does not appear in the calculations. In order to provide an output that it is in phase with the system voltage, the steady-state real current should be zero. When the firing of the shunt converter valves accomplishes the firing angle 0°, the steady-state real current is going to be zero. According to this situation, some results are obtained as follows:

When the firing of the valves is temporarily advanced, V_s would lead V_{sh}. The real power is transferred from the capacitance to AC network and then the capacitor voltage is reducing. When the firing is retarded from its steady state value, the real power would be transferred from AC network into the capacitor. The firing angle reverts to zero, when the required voltage is reached to provide the desired reactive power. The charging or discharging of the capacitor voltage can enhance the transient response time. Particularly, a large value of capacitance used in the shunt converter causes large unbalances. It is desired situation sometimes, principally for design of the STATCOM. It is used at the sub-transmission or distribution level that the reactive power changes without the variation of the DC bus voltage. In the STATCOM, which Pulse Width Modulation (PWM) is used, the reactive power can be regulated with Sinusoidal Pulse Width Modulation (SPWM) controller and selecting the proper modulation index without affecting the DC voltage. The study principle of PWM is examined in details at Appendix C.

The real power is required to change the capacitor voltage. It can only be achieved by a phase shifting between the shunt converter and AC system voltages. Hence, the phase angle δ between the AC side voltage and fundamental component of the switched voltage on the valve side of the transformer is changed to control the DC capacitor voltage in this control mechanism. The angle in phase with the positive sequence of the fundamental AC waveform is generated by using a Phase-Locked Loop (PLL) which is locked to the phase of AC system voltages.

The equations (4.3) and (4.6) point out the method to make a decoupled control mechanism in which the reference of the real power P^* does not affect the reference of reactive power Q^* and vice-versa, if the transmission line is considered to be a pure reactance with no losses. The quantity $\Delta V\cos(\phi)$ (direct axis) and the quantity $\Delta V\sin(\phi)$ (quadrature axis) of the injected voltage vector can be considered as real and imaginary components respectively. By using same equations, it can be deduced that the Q component of the injected voltage affects only the real power flow and the D component of the injected voltage affects only the reactive power flow in the line.

When voltage level of DC capacitor is dropped from its reference value, the real power is required to restore its voltage at nominal level, and it is drawn from the line. This shows that dc voltage level is signed to the required real power. Likewise, bus voltage level, where the converter is connected, is signed to the required reactive power (Kannan *et al.* 2004; Uzunovic *et al.* 1999; Kalyani *et al* 2003). Figure 4.5 shows the control mechanism of the shunt converter used in this thesis.

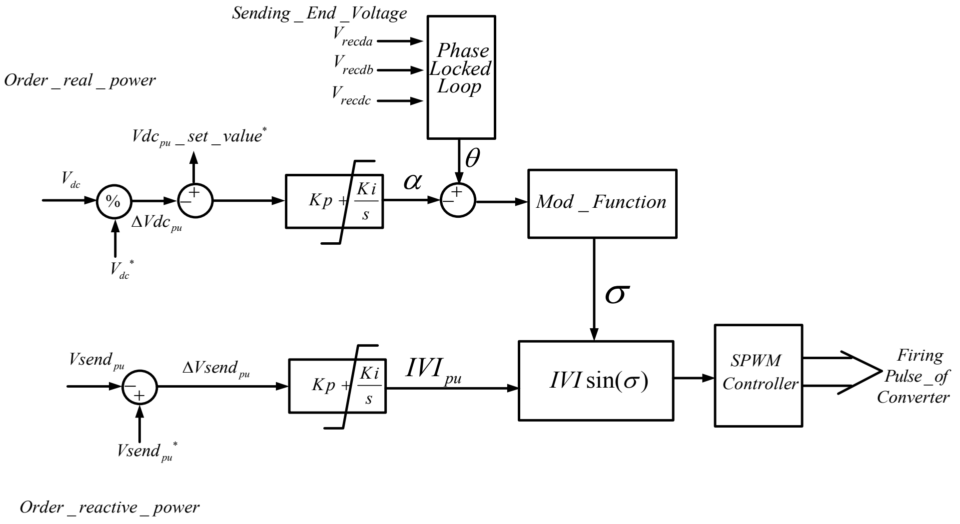


Figure 4. 5 The control mechanism used in the shunt converter in thesis

Measured DC capacitor voltage level (V_{dc}) is divided to its reference value and compared with its set value. Similarly, sending end bus voltage is measured in form of pu ($Vsend_{pu}$) and compared with its reference value. PI controller is used for obtained err values to draw their reference values. Obtained signals are compared with triangle carrier signal to produce pulses in the SPWM.

4.3.2 Control Methods of Series Converter

The magnitude and phase angle of series-injected voltage is controlled by series converter to provide the desired real and reactive power flow in the transmission line. The control methods are studied mainly for the following reason to supply the independent control for real and reactive power flow in the transmission line. The magnitude and the phase angle of the injected voltage ($\Delta V\cos(wt+\phi)$) for any desirable real P^* and reactive power Q^* are determined by using the equations (4.9) and (4.10). From the equations (4.5) and (4.8), it is seen that the term $\Delta V\cos(wt+\phi)$ denotes as a real power and the term $\Delta V\sin(wt+\phi)$ denotes as a reactive power. In other word, the D component of the injected voltage affects the real power flow and the Q component of the injected voltage affects the reactive power flow in the line. The DQ transform is used in the control mechanism of SSSC and it gives good results on controlling the real and reactive power flow in the line.

The real and reactive powers of system are measured and then compared with their reference values in the control strategy of series converter generally (Kannan *et al.* 2004; Zhou *et al.* 2004; Kalyani *et al.*2003). In reference (Nguyen *et al.* 1998), the phase angle of the system voltage is found via PLL and compared with its reference value. This technique is improved for Dynamic Voltage Restorer (DVR) and used in series converter with adding new properties in this thesis is shown in Figure 4.6.

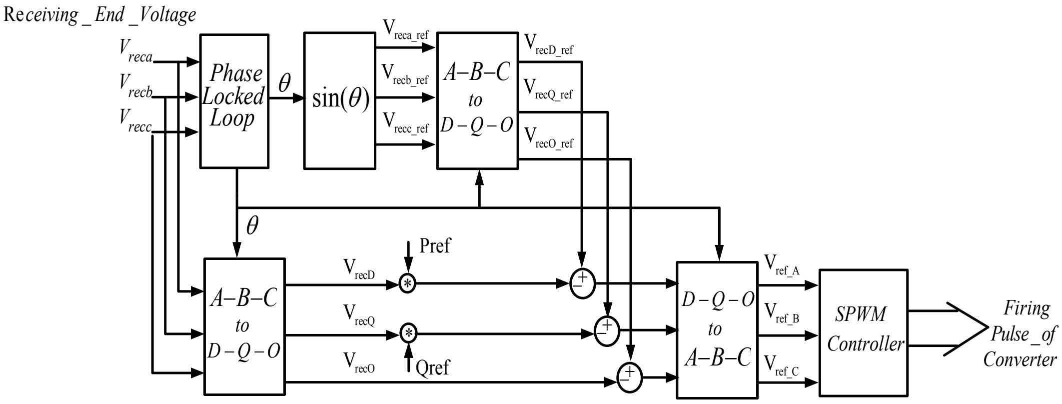


Figure 4. 6 The control mechanism used in the series converter in thesis

The signal θ is obtained by PLL which tracks the voltage of the receiving end voltage. It is used to produce $\sin(\theta)$ for DQ transform. Hence, the reference signals are obtained. The signals measured from receiving end voltage are transformed into a synchronously rotating orthogonal system (DQ transform) by using ABC-to-DQ block. These signals are compared with reference signals and the error signals are obtained. These error signals are transformed from synchronously rotating orthogonal system into three-phase balanced system again and utilized to generating pulses for series converter.

4.4 Controllers Used in Performance Analysis of UPFC

The UPFC affects the power flow in the system. The controllers used in the control mechanism of series and shunt converter perform significantly role on affecting the power flow in the system. The types of controller are very important on performance of UPFC. In literature, several controllers are improved and used in the control mechanism of UPFC. Generally, PI and fuzzy controllers are used. The fuzzy controller is improved and used in this thesis.

In many control applications, the feedback control is used. The benefits of this control method are that it is possible to keep some physical quantity at a strict level or change the value of the quantity, pressure, temperature etc, quickly and despite of the disturbances that might occur. The basic requirement that a control system should be able to fulfill is stability. This means that a controlled system should remain stable in all circumstances. The Figure 4.7 shows the principal structure of feedback control. The output signal must be followed the reference signal as precisely as possible in the feedback control. We measure the output of the process and create an error signal ($e = r - y_m$). Error signal is an input signal for the controller. The controller creates the control signal (based on the error signal) and controls the process (actually the controller controls an actuator which controls the process).

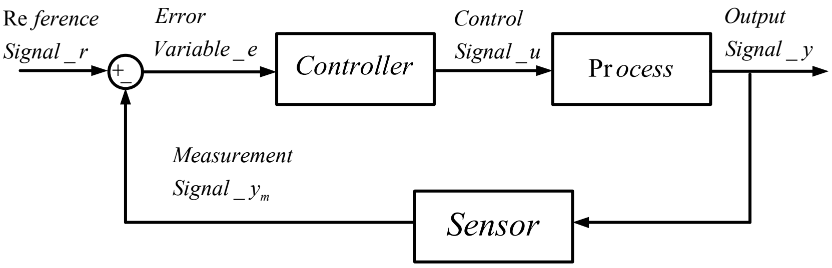


Figure 4. 7 Principal structure of feedback control

The proportional term (P) gives a system control input proportional with the error. Using only P control gives a stationary error in all cases except when the system control input is zero and the system process value equals the desired value.

The integral term (I) gives an addition from the sum of the previous errors to the system control input. The summing of the error will continue until the system process value equals the desired value and these results in no stationary error when the reference is stable. The most common use of the I term is normally together with the P term, called a PI controller. Using only the I term gives slow response and often an oscillating system.

The derivative term (D) gives an addition from the rate of change in the error to the system control input. A rapid change in the error will give an addition to the system control input. This improves the response to a sudden change in the system state or reference value. The D term is typically used with the P or PI as a PD or PID controller. The D term essentially behaves as a high pass filter on the error signal. Thus, easily introduces instability in a system and make it more sensitive to noise**.**

4.4.1 Proportional Controller (P)

In P-control, the output of the controller (control signal) is directly proportional to the error signal. Simple P controller used in control mechanism is shown in Figure 4.8.

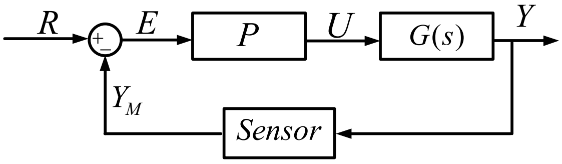


Figure 4. 7 Basic scheme of P Controller

$$U = K_e(t) \tag{4.15}$$

From equation 4.15, K is controller’s gain. Often P-control is not enough to make the output go to reference and there will be steady-state deviation.

4.4.2 Proportional Integral Controller (PI):

In PI-controller, there is another term in the controller equation shown in Figure 4.9.

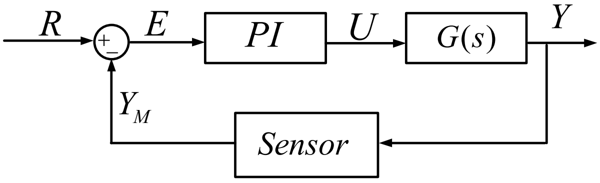


Figure 4. 8 Basic scheme of PI Controller

$$U = K(e(t) + \frac{1}{T_1}\int_o^t e(t)dt) \tag{4.16}$$

From equation 4.16, T_I is integration time constant. If the controller is tuned to be slow and T_I is large, then the controller first acts like P-controller, but later the as the integration starts to affect, the steady-state deviation goes slowly to zero. In PI-control, the steady-state deviation will finally go to zero. If the controller is tuned to be fast and T_I is small, then both terms (P and I) affect the control signal all the way from the beginning. The system becomes faster, but the output signal might oscillate.

4.4.3 Proportional Integral Derivative Controller (PID)

The equation of PID-controller has three terms. These are P, I and D-terms. Simple PID controller used in control mechanism is shown in Figure 4.10.

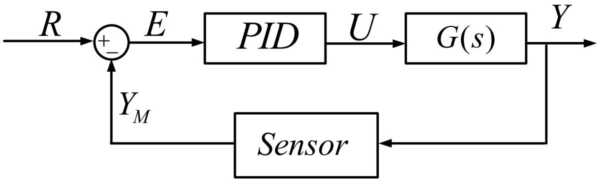


Figure 4. 9 Basic scheme of PID Controller

$$U = K(e(t) + \frac{1}{T_1}\int_o^t e(t)dt + T_d \frac{de(t)}{dt}) \tag{4.17}$$

From equation 4.17, T_d is derivation time constant. The derivation term acts like predictor, because the speed of change of the error signal affects the control signal. The derivation term has a large effect in systems where disturbances are present, because disturbances are often fast. This means that fast changes in error signal (disturbances) might even push the process to unstable state. On the other hand, the D-term might speed up the controlled system.

4.4.4 FUZZY Controller

The mathematical foundations of fuzzy theory are introduced by Lotfi Zadeh, professor at the University of California at Berkley, and the fuzzy algorithm is used first in the control system by Mamdani. The mathematical model of the control process is complexity processing. The FLC gets a new additional idea on control theory. The simple rule based on *if x and y then z* approach is incorporated to a solving control problem rather than attempting to model a system mathematically by FLC. In this thesis, a new method for the generation of reference line voltage angle for a UPFC is adopted to the control system. The proposed method does not contain any transformations. The error signal obtained from comparison of sending end voltage and its reference voltage in pu are directly processed into FL controller to improve the response time of UPFC. In this thesis, the number of rules is increased from 1 to 49 to achieve better performance. The effects of UPFC on the power system are increased by the proposed fuzzy controller. The two real time inputs are used in FLC. They are measured at every sample time and named as error and error rate. And one of the outputs is named as actuating signal for each phase. The input signals are fuzzified and represented in fuzzy set symbols by membership functions. The output (actuating) signals are produced by defined *If ... then ...* rules and these signals are defuzzified as analog control signals to compare with a carrier signal. The obtained signals are used to control the PWM converter. The details of proposed control system are given as follow:

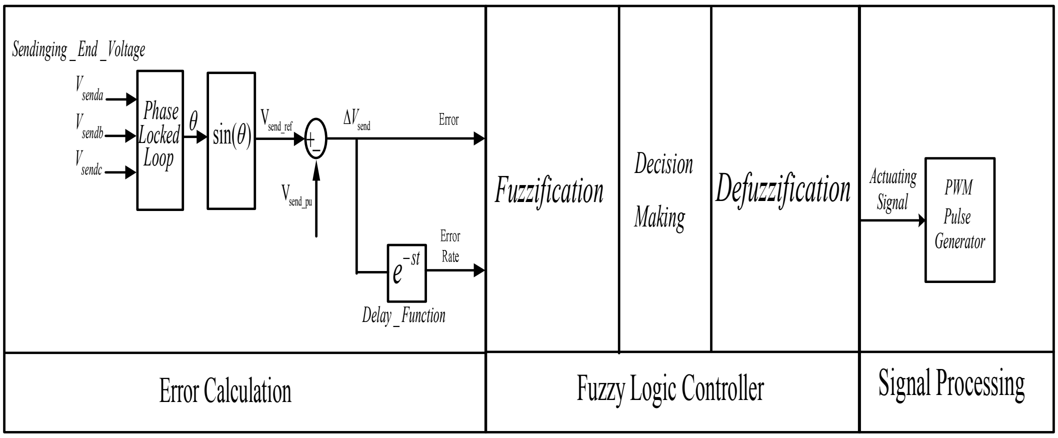


Figure 4. 10 The basic principle of preferred control system

- *Error Calculation*: The signals of supply voltage for each phase are measured and converted into per-unit value. The error is calculated from the difference between source voltage data and reference value obtained from PLL as shown in Figure 4.11. The rate error derivations are called as error rate. For phase A, the error and error rate are defined as:

$$err_A = V_{\sin(\theta)_{pu}} - V_{send_{pu}} \tag{4.18}$$

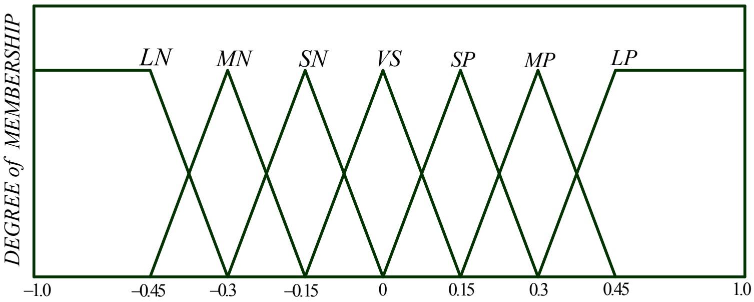
$$\Delta err_A = err_A(n) - err_A(n-1) \tag{4.19}$$

$V_{\sin(\theta)_{pu}}$ is the PLL voltage possessed the same phase with the sending end voltage. $V_{send_{pu}}$ is the phase of sending end voltage. n is the sampling time.

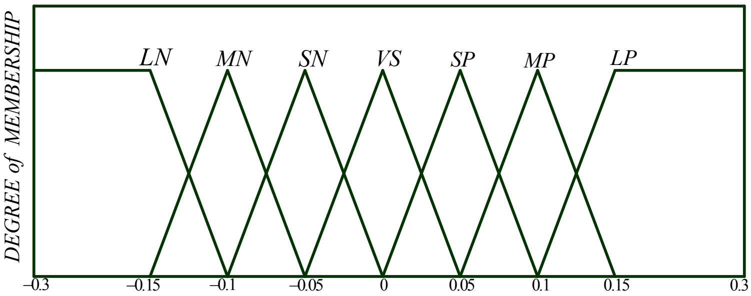
- *Fuzzy Logic Controller:* The FLC includes three steps. These detailed descriptions of each step are explained as follow:

Fuzzification: The non-fuzzy (numeric) input variable measurements are transformed by fuzzification part into the fuzzy set (linguistic) variable, which is a clearly defined boundary, without a crisp (answer). The error and error rate are described as linguistic variables such as large negative (LN), medium negative (MN), small negative (SN), very small (VS), small positive (SP), medium positive (MP) and large positive (LP). These variables are characterized by memberships in this simulation study. The curves show each membership that defines how each point is mapped to a membership value between 0 and 1 value in the input space.

The inputs signals are matched according to the appropriate membership functions. The triangular, trapezoidal, bell shaped and constant functions are used most commonly as a membership function. The number of curves and their placement are generally more important than the shape. The numbers of curves can change from three to seven. These quantity numbers of curves are generally appropriate to cover the required range of an input value. The distribution of input membership functions is uniform, which is listed in Figure 4.12.



A) ERROR



B) ERROR RATE

Figure 4. 11 The error and error rate of fuzzy membership functions

From one state to the next state, the input state variables do not change anymore via this scheme, and the membership functions change gradually from one state to the next state. The exact amount of overlap is desired state, otherwise the controller may get insufficient defined states, where it does not return a well-defined output. The weights of input membership functions are seen in Table 4.1.

Table 4. 1 The weights of the input membership functions

Input	Error	Error Rate	Function
LP	[0.3 0.45 1 1]	[0.1 0.15 0.3 0.3]	Trapezoidal
MP	[0.15 0.3 0.45]	[0.05 0.1 0.15]	Triangular

SP	[0 0.15 0.3]	[0 0.05 0.1]	Triangular
VS	[-0.15 0 0.15]	[-0.05 0 0.05]	Triangular
SN	[-0.3 -0.15 0]	[-0.1 -0.05 0]	Triangular
MN	[-0.45 -0.3 -0.15]	[-0.15 -0.1 -0.05]	Triangular
LN	[-1 -1 -0.45 -0.3]	[-0.3 -0.3 -0.15 -0.1]	Trapezoidal

The trapezoidal (Trapmf) and the triangular (Trimf) membership functions are used in the fuzzy controller as input membership functions. These functions must be chosen to satisfy the output needs of the fuzzy controller.

Decision Making: The inference of fuzzy process is carried out by both Mamdani and Takagi-Sugeno methods. A highly non-linear functional relation can be expressed by Takagi and Sugeno's model using a small number of fuzzy rules. It works well with linear techniques, and is fitted for modeling non-linear systems by using the interpolating multiple linear models. The fuzzy models are created by using Sugeno system. The *ith* rule is given in the following form.

$$\begin{aligned} &L^{(l)} : \text{If } x_1 \text{ is } F_1^l \text{ and .... and } x_n \text{ is } F_n^l \text{, then} \\ &y^l = c_0^l + c_1^l x_1 + c_2^l x_2 + \dots + c_n^l x_n \end{aligned} \tag{4.20}$$

The term of fuzzy set is F_i^l; The term of real valued parameter is c_i^l; The terms of the system output owing to the rule is c_i^l; The term of the real valued inputs are $x_1, \dots, x_n$; l = 1, 2, 3…M.

The basic if-then rule is defined as follows:

If (error is A and error-rate is B) then output $y = B$

The linguistic value specified by fuzzy sets on the range error is A. The linguistic value specified by fuzzy sets on the range error-rate is B. The output is y. The more complex rule is clearly characterized as follow:

If (error is very small and error rate is very small) then output

$$y = a * error + b * error \cdot rate + c \tag{4.21}$$

Here, a, b and c are constant value.

The Fuzzy Inference System (FIS) where the input is connected to the output is defined by the if-then rules. Sugeno inference method can be achieved easily by relationship between its inputs and outputs. The outputs are characterized by memberships and named as linguistic variables such as negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive big (PB). The membership functions of output variables are shown in Figure 4.13.

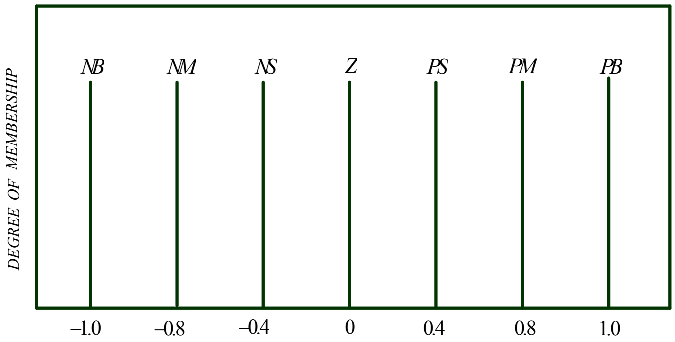


Figure 4. 12 The output of fuzzy membership functions

Table 4. 2 The table of fuzzy decision

Error rate /Error	**LP**	**MP**	**SP**	**VS**	**SN**	**MN**	**LN**
LP	PB 1	PB 2	PB 3	PM 4	PM 5	PS 6	Z 7
MP	PB 8	PB 9	PM 10	PM 11	PS 12	Z 13	NS 14
SP	PB 15	PM 16	PM 17	PS 18	Z 19	NS 20	NM 21
VS	PM 22	PM 23	PS 24	Z 25	NS 26	NM 27	NM 28
SN	PM 29	PS 30	Z 31	NS 32	NM 33	NM 34	NB 35
MN	PS 36	Z 37	NS 38	NM 39	NM 40	NB 41	NB 42
LN	Z 43	NS 44	NM 45	NM 46	NB 47	NB 48	NB 49

In the fuzzy controller used in this thesis, the symmetric AC variables which posses both positive and negative half-waves are used in order to get the effective control accuracy and the simple based rule. The rules are created by taking into account both positive and negative half-wave polarity of the system variables. This may be visualized as the third controller input variable. These variables are used to switch between two rule tables at every zero-axis crossing of the reference voltage. The decision tables for fuzzy logic control rules are shown in Table 4.2.

The seven membership functions are defined as an each input of the fuzzy system above. Consequently, the fuzzy system consists of $7^2=49$ rules. Optimum control action is achieved by these rules, and the operating conditions of the system are expressed by each rule.

The rules are defined by taking help from person's experience and knowledge about the plant behavior. All the rules are evaluated in parallel, and the range of the rules is not important. The performance of the system is improved by the correct combinations of these rules. The algorithm for generating the appropriate control action can be thought as follows:

The voltage error (magnitude and sign) shows the system condition. If it is large (small), it means that the voltage is far (near) from its reference value; if it is positive (or negative), it means that the phase voltage is smaller (or bigger) than the reference value. The sample rule is given from Table 4.2 as follow:

Rule 20: IF the error is (SP) AND error rate is (MN), THEN the output is (NS).

The accuracy of the control system can be improved by increasing the number of rules, but the data size or the complexity of the control system can be increased. The output is evaluated according to the all rules and produced by the fuzzy sets and the fuzzy logic operations. The initial step is to take the inputs and determine their degrees according to the input degrees belonging to appropriate fuzzy sets by using membership functions. Once the inputs progress in the fuzzified processing, the degree which each part of the antecedent has been completed for each rule is obtained. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to gather into one part. This part represents the result of the antecedent for that rule, and then it will be applied to the output function. The inputs given to the fuzzy operator are formed by combining two or more membership values from fuzzified input variables. The output is a single truth value.

Defuzzification: In the defuzzification processing, the controller outputs represented as linguistic labels by fuzzy set are converted to the real control (analog) signals. Sugeno's weighted average (wtaver) method, which is the special case of Mamdani model, is selected for defuzzification. The output of the Sugeno fuzzy system is a weighted average of the outputs for all the rules. The solution of defuzzification process results from equations (4.22) and (4.23).

$$y = \frac{\sum_{l=1}^{M} w^l y^l}{\sum_{l=1}^{M} w^l} \tag{4.22}$$

$$w^l = \prod_{i=1}^{n} M_{F_i^l}(x_i) \tag{4.23}$$

$x_1.........x_2$ is real valued inputs and y is the output of the Sugeno fuzzy system; the overall truth value of the term of the rule $L^{(1)}$ is w^l; the membership function that describes the meaning of the linguistic value F_i^l is $M_{F_i^l}$.

- *Signal Processing*: The control signals are produced from the outputs of FLC process that are used in generation of switching signals for converter by comparing a carrier signal as shown in Figure 4.14.

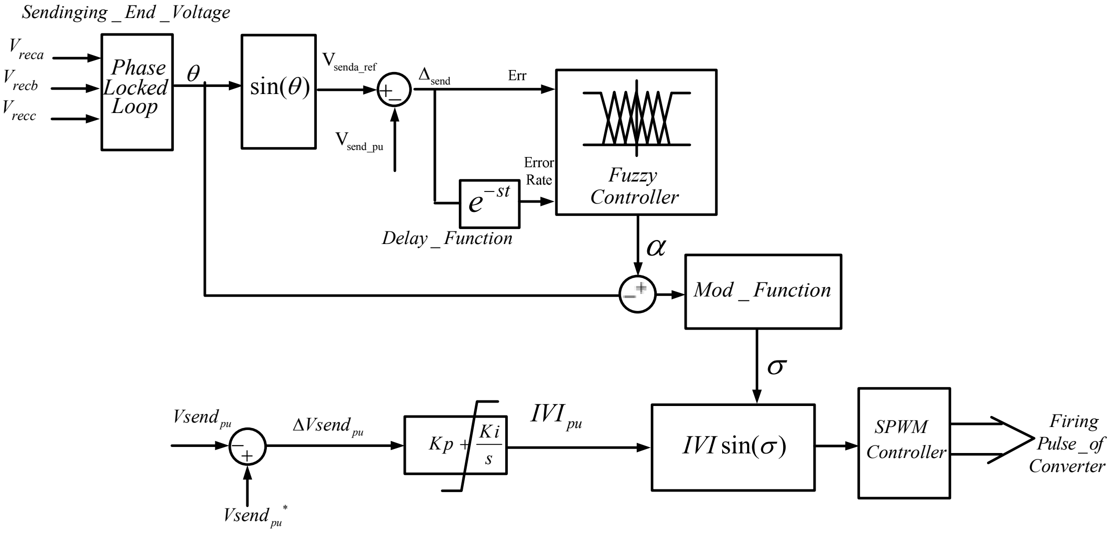


Figure 4. 13 Generation of PWM switching signals using fuzzy Controller

The PLL component is used to obtain the signal θ by racking the receiving end voltage and the signal is used in $\sin(\theta)$ block to obtain reference signal for sending end in pu. The reference signal is compared with signal measured from sending end voltage, and hence error value of voltage (Err) is obtained. The error value and its retarded value are used in fuzzy controller to produce signal α. The signals α and θ

are used in mod function to obtain signal σ. The signals $V_{send_{pu}}$ and V_{send} are compared to obtain the amplitude signal IVI_{pu}. The signals IVI_{pu} and α are used to generate firing pulses of shunt converter. Both the fuzzy controller and carrier signal, also the maximum and the minimum values of input signals are set as 1 and -1, respectively. The frequency of carrier signal is set as 3 KHz.

4.5 Conclusion

General mathematical information of power flow incorporated with angle and magnitude of line voltage is given. And then, the mathematical equation associated with series and shunt converter of UPFC is explained. Several examples of control mechanism belonging to series and shunt converter are given, and control mechanism of series and shunt converter used in this thesis are discussed in details. The operating principle of controllers (P, PI, PID and fuzzy) are explained in the last section.

5. MODELLING OF UPFC

In this chapter, the development of a UPFC model is discussed to verify the performance of the controllers as well as network application studies in the future. Main objectives of this chapter are collected in two titles as follows.

- To build a UPFC model on PSCAD/EMTDC program to verify the steady state capabilities in the power system.
- To develop fuzzy controllers for an application in the control mechanism to verify the performance analysis of UPFC in the power system.

Generally, in the case studies, UPFC is seen to construct before the line impendence in references (Fujita *et al.* 1999; Sayed *et al.* 2007). According to this situation, UPFC is constructed before the line impedance in this thesis. Basic scheme of UPFC developed for this thesis is shown in the Figure 5.1.

The two generators having the same properties are used and named as sending end Generator and receiving end generator. Shunt converter and series converter show the same properties with STATCOM and SSSC, respectively. The technical details of sending and receiving end generators are given in Appendix E.

The sending end and receiving end generators have the same properties as well as the same phases. The phase variation can be formed under several conditions (line impedance, faults… etc.). In respect to the phase variation, power flow occurs in the line. The UPFC is used to get better utilized power flow from the line. In the simulation studies of this thesis, phase of sending end generator is kept stable while the phase of receiving end generator is changed manually to see the performance of UPFC using several controllers for power flow in the line.

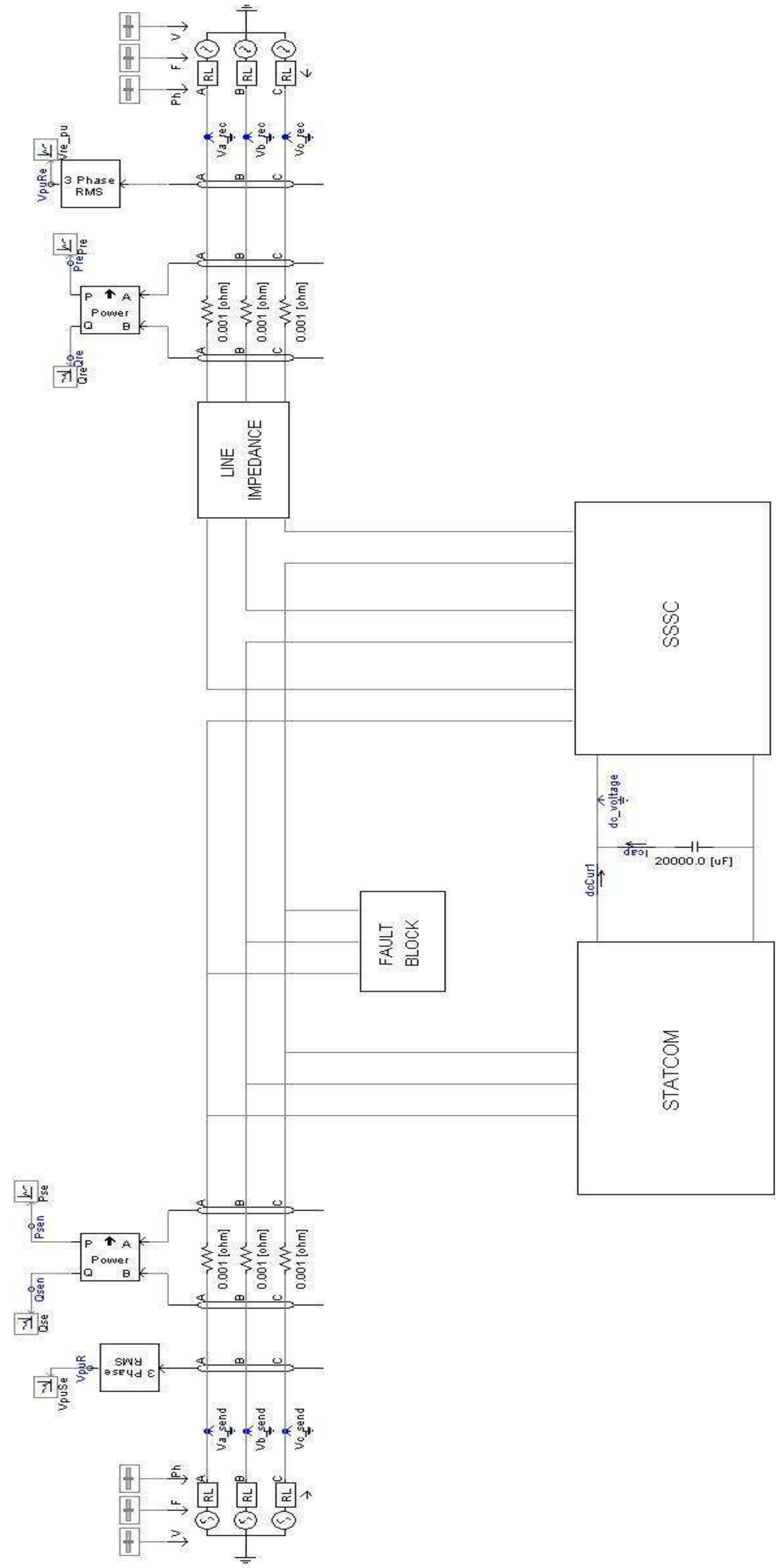


Figure 5. 1 Basic scheme of UPFC

5.1 Shunt Converter of UPFC

As mentioned before, UPFC which consists of a series and a shunt converter is connected by a common dc link capacitor. The shunt converter has shown the same function as STATCOM in UPFC. The structure of shunt converter is shown in the Figure 5.2. Two principles are fulfilled by the shunt converter listed below.

- To maintain the transmission line voltage at its reference value, reactive power is absorbed or provided from the point of line where the shunt converter connected.
- To maintain DC voltage levels at its reference value by drawing the real power from the line.

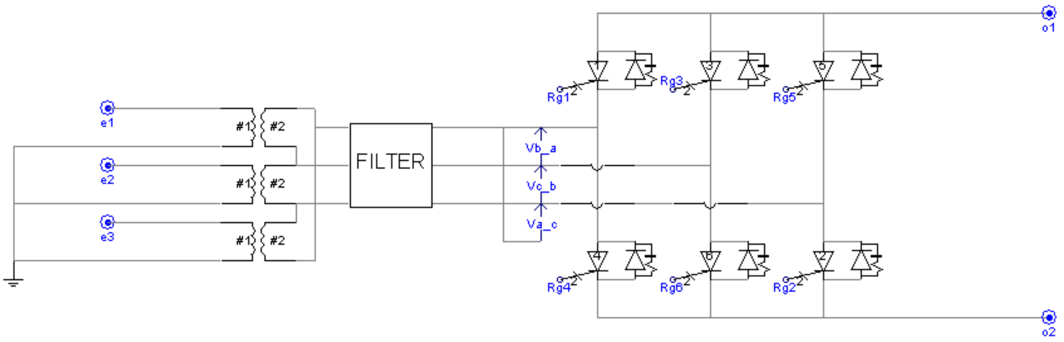


Figure 5. 2 Structure of shunt converter

The Insulated Gate Bipolar Transistors (IGBT) is used in the structure of the converter. The harmonics are generated from converter naturally when firing pulses are given to gates of IGBT. Some passive filters and coupled transformers are used to protect the system from these harmonics, such as short circuit. The technical details of coupled transformers are given in Appendix E.

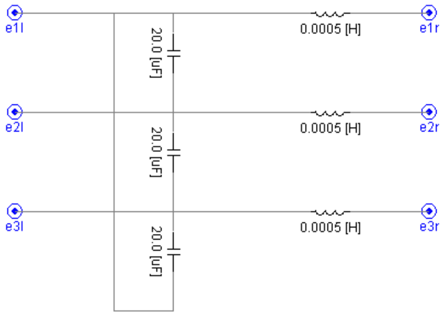


Figure 5. 3 Passive filters used in shunt converter

The passive filters are used for three phases either to protect the system or to eliminate the harmonics generated from converter naturally. These three phase filters are shown in the Figure 5.3.

The reference sinusoidal signals generated from control mechanism of shunt converter are compared with carrier signals shown in the Figure 5.7. The results of these signals are firing angle of IGBT shown in the Figure 5.6.

5.1.1 Control Mechanism of Shunt Converter

The control mechanism of shunt converter is mentioned in chapter 4. It is actualized in PSCAD/EMTDC program shown in the Figure 5.4 to 5.7. The real power is drawn from the line to keep the capacitors voltage level at specified value. It is accomplished by the way of changing the angle of the shunt converter output voltage. When the angle of shunt converter is retarded from the line, the power is drawn from the line to converter. When the angle is forwarded from the line, the real power is given from the shunt converter to the line. Hence, DC voltage level is adjusted according to its reference value.

When faults (ground, short circuit… etc.) are occurred at the bus (sending end) connected the shunt converter, bus voltage level drops from its nominal value. The shunt converter accomplishes from this situation by changing its output voltage magnitude. The reactive power is drawn or given from the shunt converter to the line when bus voltage magnitude is dropped or increased.

The reactive power is drawn from the line to compensate the bus voltage by shunt converter when bus voltage magnitude is bigger than its reference value. Also reactive power is given from shunt converter to line when bus voltage magnitude is dropped from its reference value. The control mechanism of shunt converter is applied according to references (Padiyar *et al.* 1998; Kannan *et al.* 2004), in this thesis shown in Figures 5.4 and 5.5.

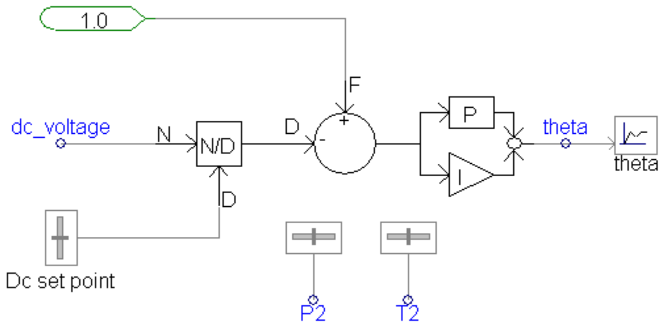


Figure 5. 4 Control mechanism of DC voltage

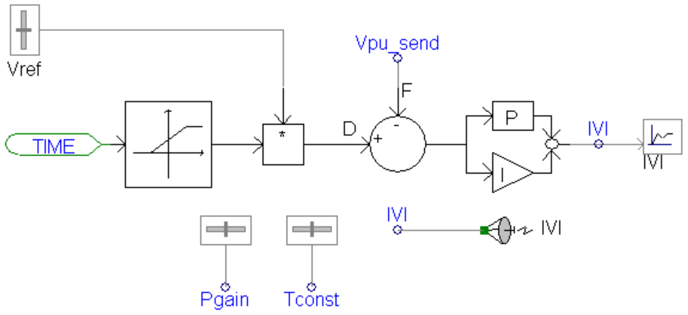


Figure 5. 5 Control mechanism of bus voltage magnitude

The DC voltage level controller is given in the Figure 5.4. The DC voltage is measured from the link between shunt and series converter. This value is divided to its reference value and result is compared with desired DC set voltage value. The obtained error value is given to PI controller to get angle *theta* for shunt converter output voltage.

The sending end bus voltage controller is shown in the Figure 5.5. The measured bus voltage from sending end is compared with its reference value. The obtained error is given to PI controller to get reference magnitude value for shunt converter output voltage.

The calculated angle and magnitude values are used to produce reference sinusoidal signal for IGBT used in shunt converter presented in the Figure 5.6.

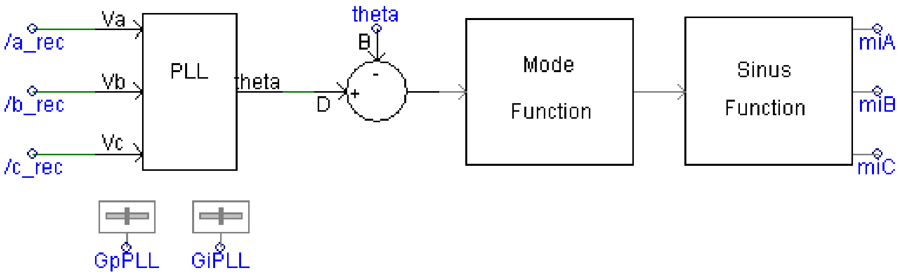


Figure 5. 6 Calculating reference signal for shunt converter

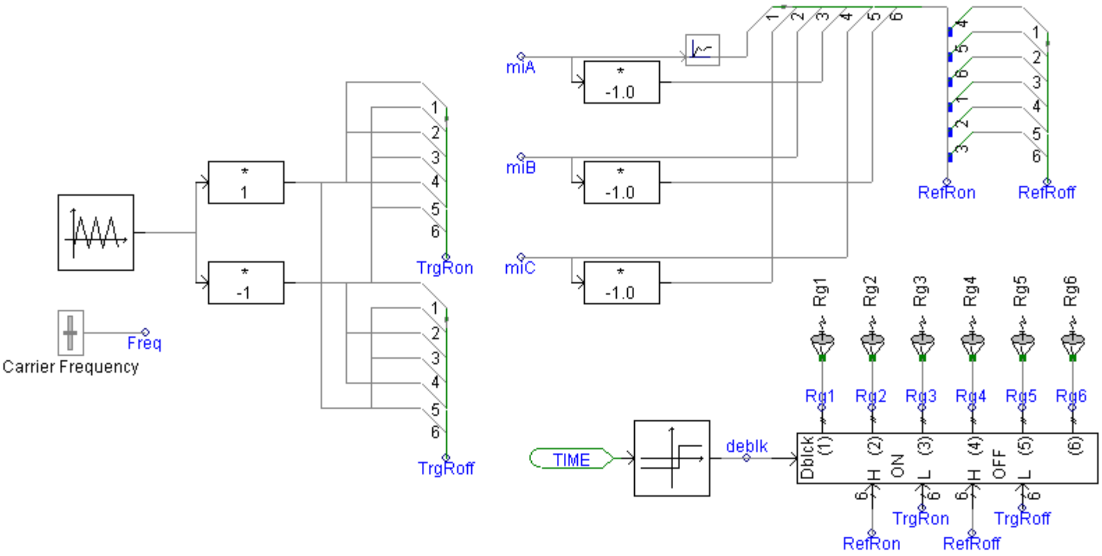


Figure 5. 7 Generating firing pulses for IGBT

The PLL is used to track the line voltage to find line angle ‘gamma’. The angles gamma and theta are passed through the modulation function block and their modulation is taken for 360^0 in this block. The result is used in sinus block to generate three phase balance reference voltage for SPWM shown in the Figure 5.7.

The obtained reference sinusoidal signals are used in the SPWM to compare with triangular carrier signal to generate firing pulses for IGBT. These signals are named as *RetRon* and *RetRof*. The generated from triangular block are named as *TrgRon* and *TrgRof*, at 3500 KHz frequency. The reference signals and carrier signals are compared in the *Interpolated Firing Pulse* block to produce firing angle for IGBT given in the Figure 5.7.

5.2 Series Converter of UPFC

The shunt and series converter are worked independently from each other. The series converter has same properties with SSSC. It controls the series converter output voltage to get the better utilized power flow in the line using DC voltage. As the DC voltage is used by series converter, it is important to keep stable voltage level. Considering this situation, shunt converter maintains DC voltage level at its reference value mentioned above. The structure of series converter is given in the Figure 5.8.

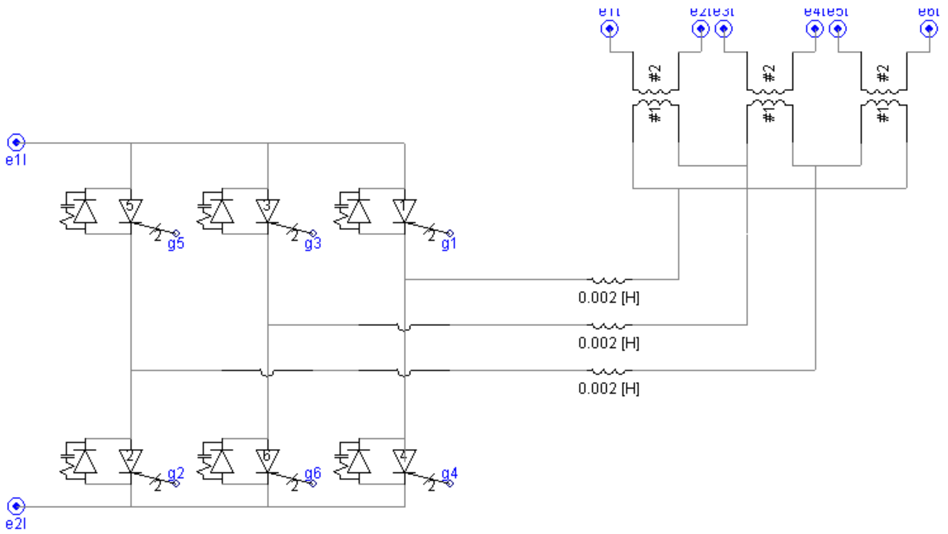


Figure 5. 8 Structure of series converter

The coupled transformers and six pulses converter are used for same purpose as shunt converter. The capacitance value is selected as 20 mF. The technical details of series transformers are given in Appendix E.

5.2.1 Control Mechanism of Series Converter

The control mechanism of series converter is mentioned in chapter 4. It is actualized by depending on reference (Nguyen *et al.* 2004), shown in the Figures 5.9 and 5.10. PLL is used to track the receiving end voltage to generate reference angle for series converter. The obtained the angle is given to sinus block to generate reference sinusoidal signal. The synchronous three phase system is converted to the orthogonal system by using ABC to DQ block. According to this, ABC to DQ block is used to convert reference sinusoidal signal to its DQ form shown in the Figure 5.9.

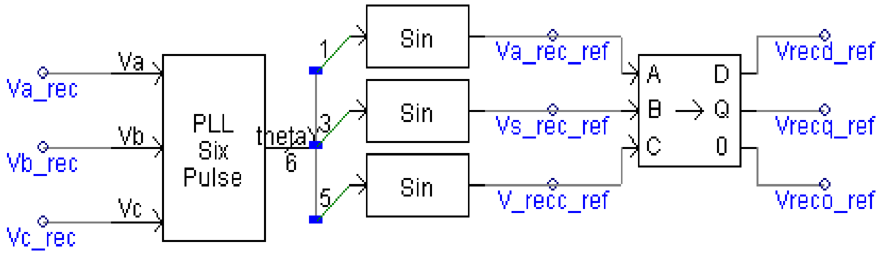


Figure 5. 9 Generating reference signal for series converter

The measured signal from receiving end voltage is converted to its DQ form using ABC to DQ block in PSCAD/EMTDC program shown in the Figure 5.10.

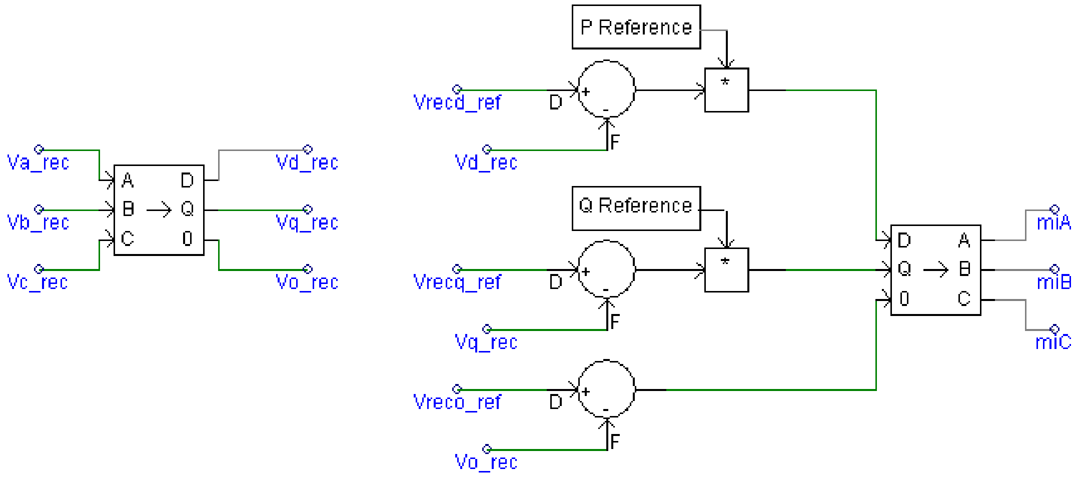


Figure 5. 10 Generating reference signal for series converter

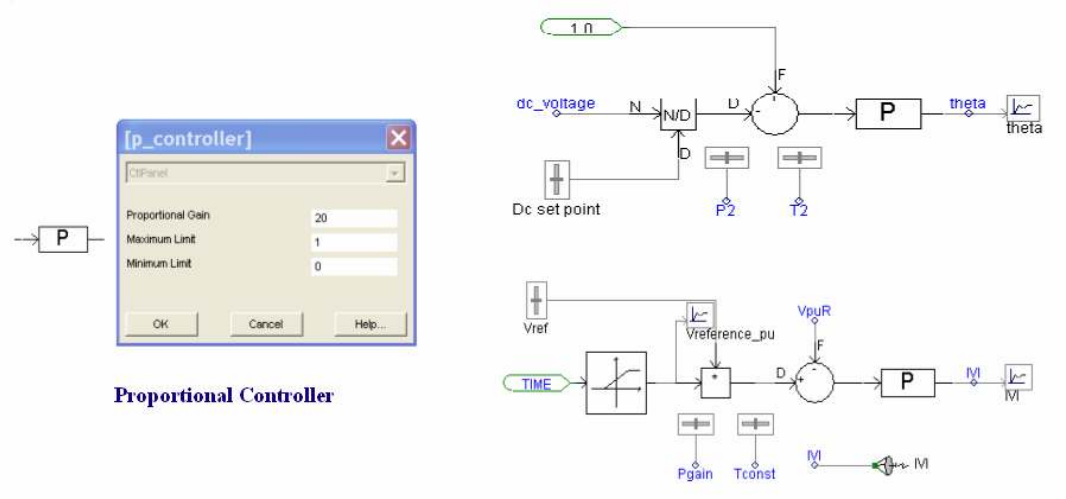
The DQ form of receiving end voltage and its reference values are compared. The error signals are multiplied with real and reactive power references. The obtained signals are transformed to balance three phase signals by using DQ to ABC block shown in the Figure 5.10. The result signals are used in SPWM in the same way as the shunt converter to generate firing angle for IGBT.

5.3 Controller Design for UPFC in PSCAD /EMTDC Program

The performance analyzing of UPFC is investigated with different types of controllers by using PSCAD/EMTDC program in this thesis. The controllers are discussed in chapter 4. Only one kind P controller exists in main library of PSCAD/EMTDC program. Other controllers are developed depending on their mathematical equation and their truth is checked out in Matlab/Simulink. The developed controllers in this thesis are listed below.

5.3.1 P Controller

The P controller is obtained by actualizing the equation $U = Ke(t)$ in the literature. It contains only P gain. According to this equation, P controller is built by considering the gain $Ke(t)$ in PSCAD/EMTDC program. The PSCAD/EMTDC program software gives opportunity to create new component by using FORTRAN codes and to build visual user interface. Also, P controller is created by using FORTRAN codes and user interface shown in the Figure 5.11. The truth of P controller is controlled with several gains in MATLAB/Simulink and reliability is provided.

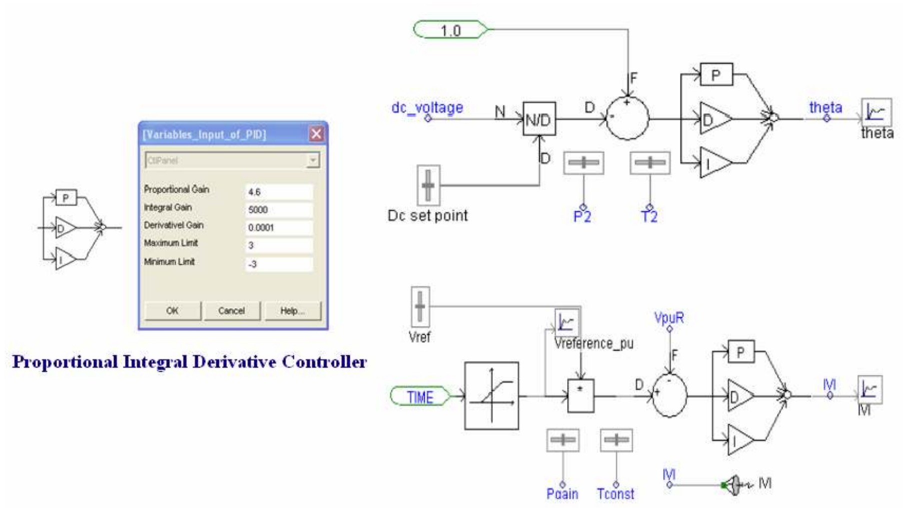


Proportional Gain 20
Maximum Limit 1
Minimum Limit 0

Figure 5. 11 Proportional controller using in the control mechanism

5.3.2 PID Controller

The PID controller is obtained by considering the equation $U = K(e(t) + \frac{1}{T_1}\int_o^t e(t)dt)$ in the literature. It contains proportional, integral and derivative gains. As PID controller does not exist in main library of PSCAD/EMTDC program, it is created and built with its visual user interface shown in the Figure 5.12. The truth of PID controller is tested with several gains in MATLAB/Simulink and reliability is provided.


[Variables_Input_of_PID]

Proportional Gain 4.6
Integral Gain 5000
Derivativel Gain 0.0001
Maximum Limit 3
Minimum Limit -3

Figure 5. 12 PID controller using in the control mechanism

5.3.3 FUZZY Controller

The details of fuzzy controller are discussed in chapter 4. The fuzzy controller is created by using FORTRAN codes and visual user interface. The created fuzzy controller is shown in the Figure 5.13 and its codes are given at Appendix D.

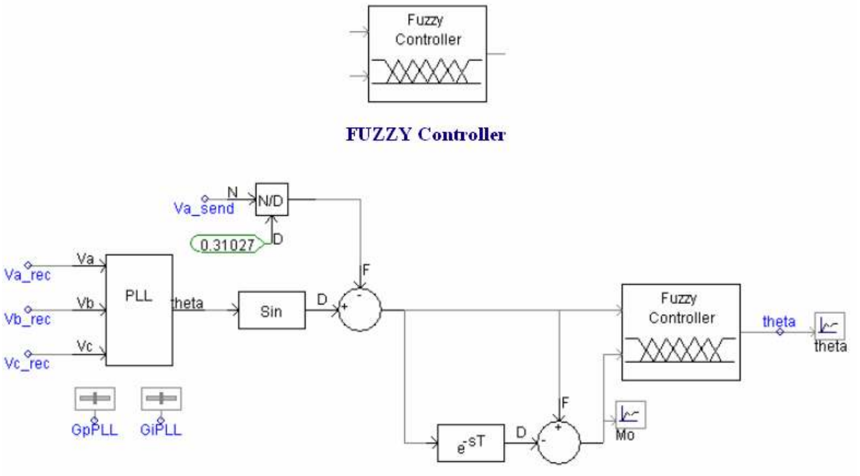


Figure 5. 13 Fuzzy controller using in the control mechanism

5.4 Conclusion

The shunt converter and series converter are modeled in PSCAD/EMTDC program. The details of its structure and control mechanism of UPFC are studied in this chapter. The developed controllers for UPFC are discussed.

6. SIMULATION EXAMPLES

The phase variation is between sending end and receiving end generators in the transmission lines. The power flow occurs according to the quantity of phase variation. Some FACTS devices are used to utilize more effectively from the power flow in the transmission line. The UPFC is the most beneficial in these FACTS devices. Generally, the power and voltage ratings are in MVA, KV, respectively in the transmission line. These power and voltage ratings could not be achieved in laboratory environment. Regarding this situation, the experimental cases are studied in references (Fujita *et al.* 2006; Sayed *et al.* 2007; Gao *et al.* 2005), and the power and voltage ratings used in the experimental systems are smaller than the real transmission line ratings. The test system has same ratings as used in references (Sayed *et al.* 2007; Gao *et al.* 2005) in this thesis. All the quantities of UPFC are based on the KVA and V (10 KVA and 380 V (line-line)).

In the case studies, the two generators having the same properties are used as a sending end and receiving end generator. $4\,\Omega$ and $0.01\,\mathrm{H}$ are selected as line resistant and inductance respectively to represent the transmission line seen in Figure 6.1. The phase variations at the receiving end generator are formed systematically to analyze the performance of UPFC with controllers on power flow. In all case studies, the generators have the same properties and the transmission line impedances use same quantities. The effects of each controller are compared to show the performance of these controllers on power flow in the line transmission.

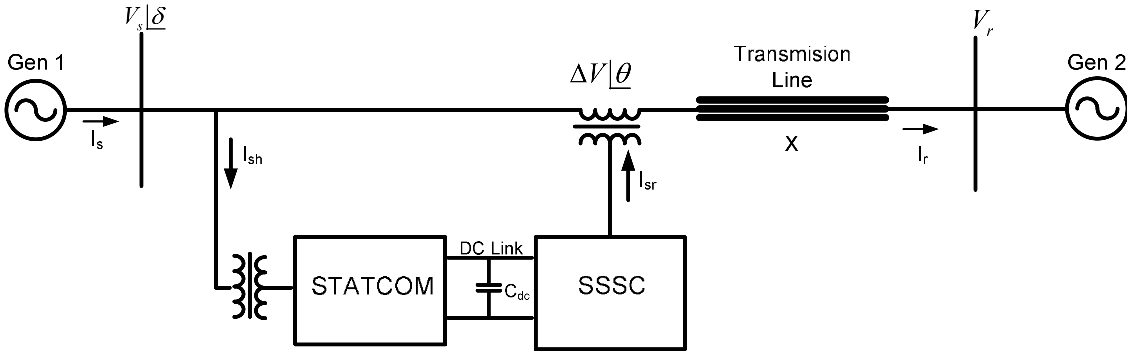


Figure 6. 1 The test system of UPFC

The simulation and experimental studies are based on the effectiveness of UPFC on power flow in the literature. However, the effectiveness of UPFC is not observed on faults so much. The case of phase-to-ground fault is studied in reference (Schauder *et al.*1998) and the series part of UPFC becomes electronic bypass immediately to protect the series converter. The behaviors of UPFC are seen on the phase to ground faults, when the phase to ground fault occurs in reference (Schauder *et al.*1998). The same faults cases are studied and the performance of controllers is compared when the 3-phase-to-ground fault is applied in the case studies 3 and 4.

6.1 Case 1

The receiving end generator is retarded from sending end generator, and the power flow of the line with UPFC and without UPFC is observed in this case. The technical details of generators are given Appendix E. The power flow is provided by retarding 30.0^0 the receiving end generator from the sending end generator. The amounts of real and reactive power are 2.1 KW and 0.7 KVAR, respectively when the system is worked without UPFC. In the same way, the real and reactive powers are 2.45 KW and 0.1 KVAR, respectively, when UPFC is activated in the line. The PI controller is used in the control mechanism of UPFC when the results are taken. These results are compared graphically in Figure 6.2 and 6.3. The reference value of P is selected as 10 and the reference value Q is selected as 1 for case studies 1 and 2.

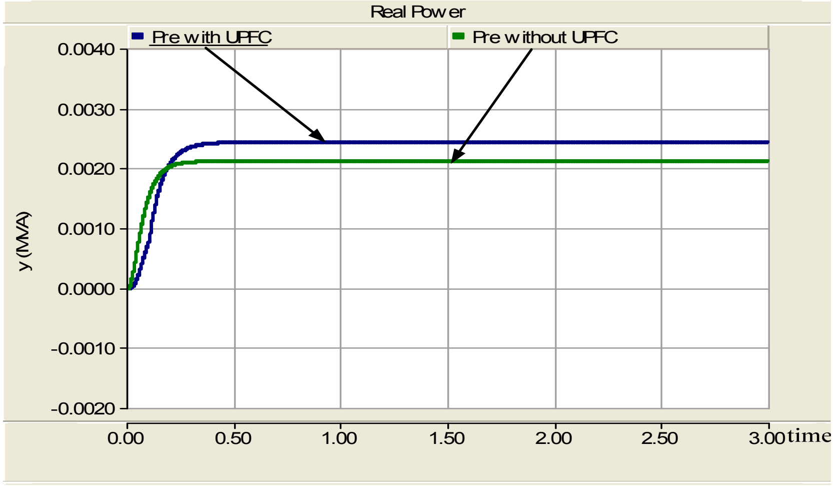


Figure 6. 2 Real power quantities of the line with and without UPFC

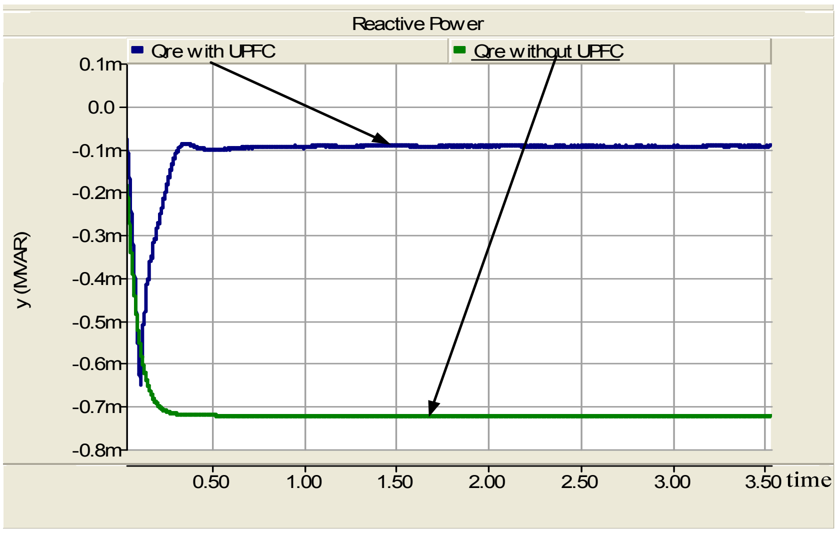


Figure 6. 3 Reactive power quantities of the line with and without UPFC

The shunt converter must fulfill two tasks when it is working as a STATCOM in UPFC. One of tasks is keeping the bus voltage connected to the line at its reference value, and the other is supplying the certain dc voltage level for series converter as a voltage source. According to this, the sending end voltage is kept stable at its reference value in per unit, and the dc link voltage is provided as 40V to supply the voltage for series converter. UPFC takes the phase angle of transmission line to minimal value as possible. Their graphics are shown in figures 6.4 to 6.7.

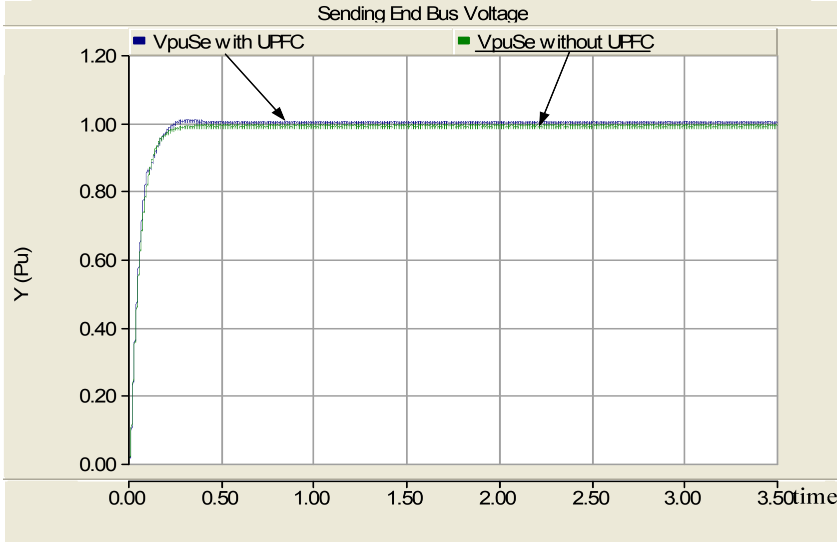


Figure 6. 4 Sending end bus voltage with and without UPFC in the line

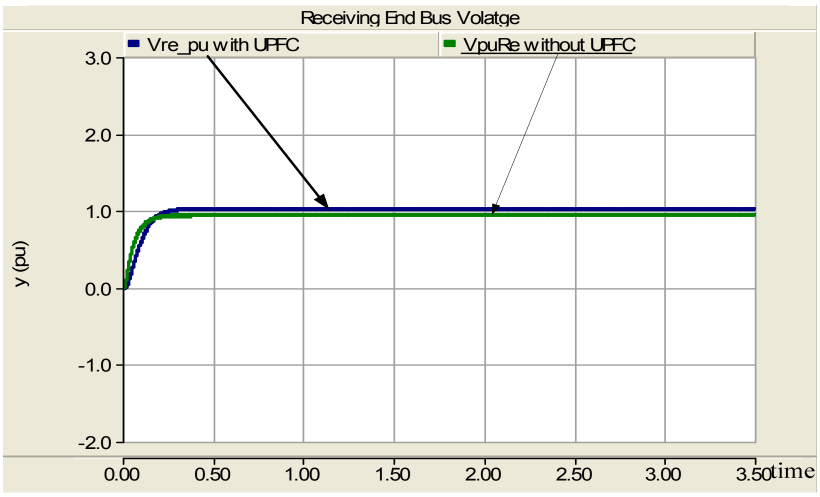


Figure 6. 5 Receiving end bus voltage with and without UPFC in the line

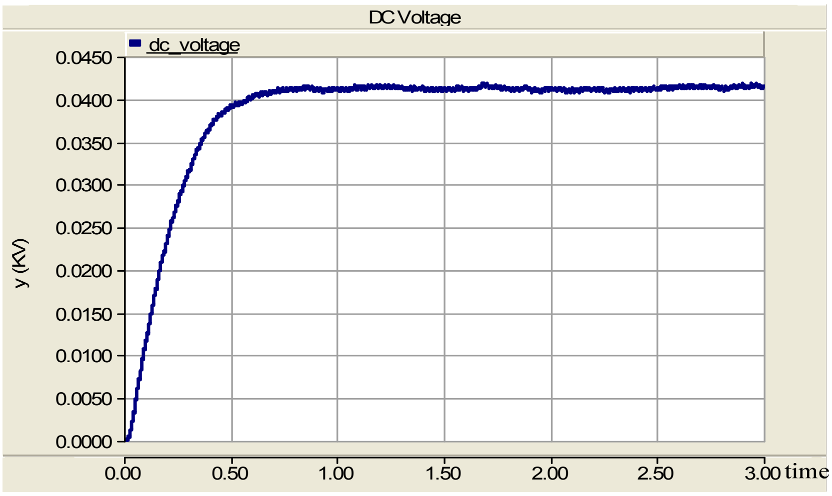


Figure 6. 6 Dc link voltage

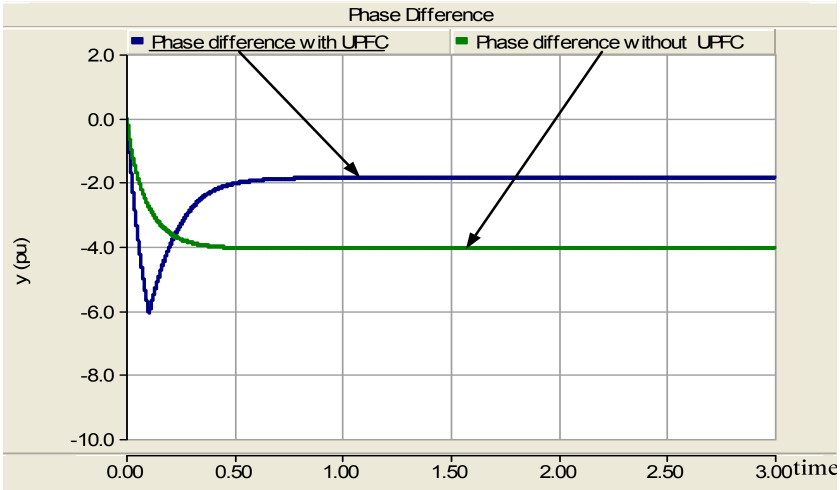


Figure 6. 7 Phase difference between busses with and without UPFC

6.2 Case 2

The direction of power flow is considered as from sending to receiving end side in the line and mathematical equations are calculated in terms of this power flow direction. In other words, from the equation 4.3 and 4.7, when the phase of receiving end generator is retarded from the sending end generator, the power flow is provided from sending end side to receiving end side. According to the performance of the controllers, the phase of receiving end generator is changed systematically and the results are compared as a power flow of the line. The results of power flow for phase variation are listed in table 6.2.

Table 6. 1 The power flow of the line for phase variations

Phase angle of Receiving end Generator (^{0})		180	210	240	270	300	320	330	345	355
Without UPFC	P(KW)	-1.39	0.90	2.78	3.72	3.44	2.67	2.11	1.11	0.38
	Q(KVAR)	-1.5	-2.10	-2.26	-2.02	-1.4	-0.97	-0.72	-0.34	-0.11
P Controller With UPFC	P(KW)	-1.50	1.70	4.03	4.70	4.00	2.95	2.29	1.21	0.45
	Q(KVAR)	-2.29	-2.82	-1.96	-1.17	-0.62	-0.42	-0.37	-0.036	-0.39
PI Controller With UPFC	P(KW)	-1.52	1.67	3.97	4.6	4.14	3.09	2.43	1.37	0.61
	Q(KVAR)	-2.26	-2.84	-1.99	-1.19	-0.42	-0.15	-0.09	0.04	0.16
PID Controller With UPFC	P(KW)	-1.54	2.03	4.37	4.94	4.15	3.06	2.4	1.35	0.61
	Q(KVAR)	-2.22	-2.78	-1.70	-0.91	-0.39	-0.21	0.14	0.01	0.16
FUZZY Controller With UPFC	P(KW)	-1.52	1.66	4.50	5.30	4.33	3.14	3.14	1.41	0.68
	Q(KVAR)	-2.25	-2.85	-1.50	0.40	-0.07	-0.08	-0.088	0.07	0.22

6.3 Case 3

As mentioned before in reference (Schauder *et al.*1998), the phase-to-ground fault occurs, and excessive current flows on phase A. In the same way, the three phase fault is applied at the sending end seen in figure 6.8. When UPFC senses fault, it immediately activates the electronic bypass to protect the series converter in case studies 3 and 4. The test system is shown in the following.

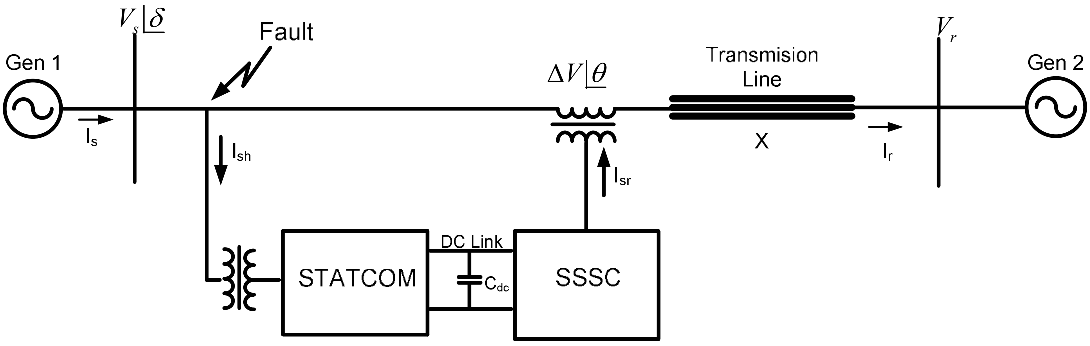


Figure 6. 8 Test system of case study 3

The fault is started at 1.4 sec and its duration is 0.2 sec in this case. The excessive current flows on the short circuit impedance 53.03+j0.1688Ω. In the control mechanism, the reference value of P and Q are selected as 1 for case studies 3 and 4. The shunt converter remains operational to supply reactive compensation to the line and the series converter is closed by breaker during the fault time. The bus voltage and the reactive power are provided to keep theirs reference and nominal values when UPFC is connected to the system. The results of reactive power quantities and receiving end bus voltage are compared graphically by using in figure 6.9 to 6.12.

Considering the results, the P controller has not effect on reactive power compensation and bus voltage control when the fault occurs. The PI, PID and fuzzy controllers are more effective than P controller when the fault appears in the line. The fuzzy controller is the most effective on power flow in these controllers.

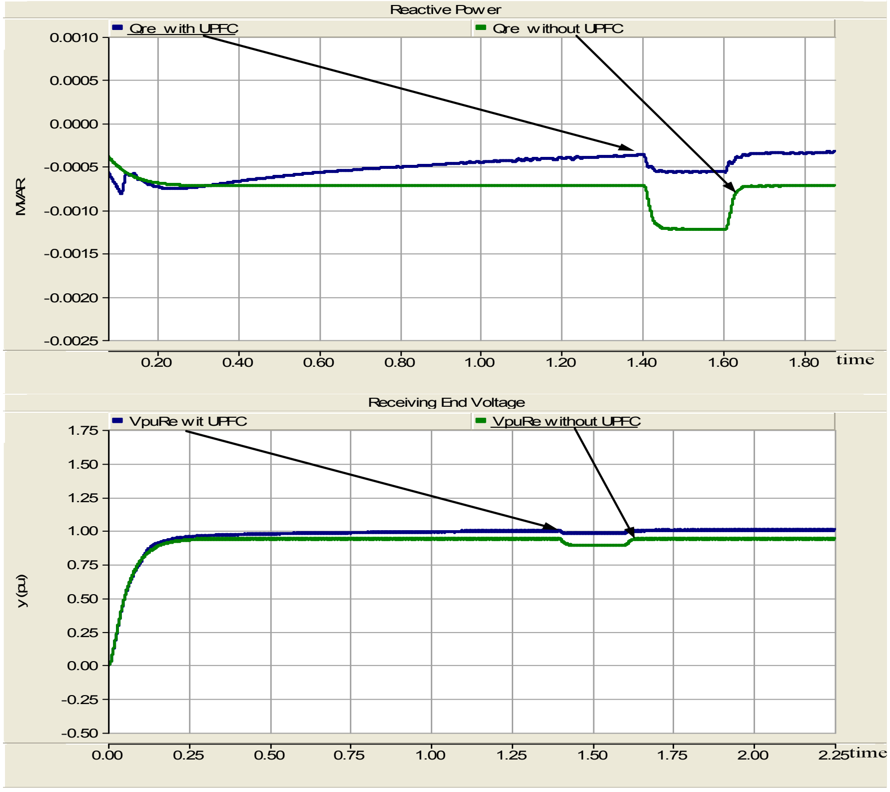


Figure 6. 9 The P controller results when the fault was occurred

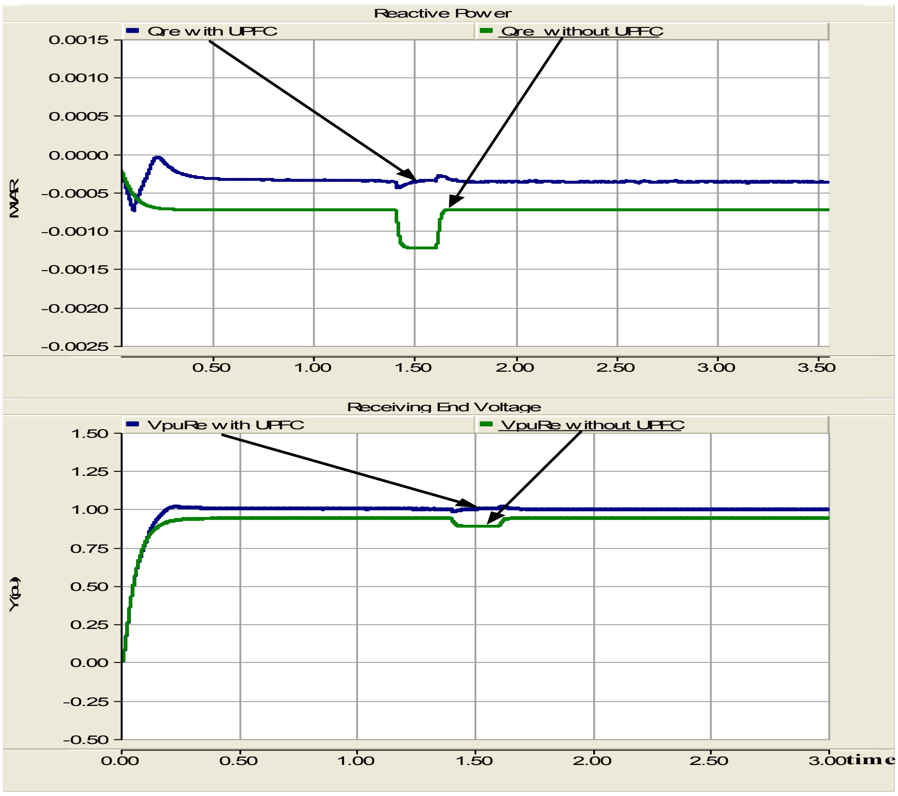


Figure 6. 10 The PI controller results when the fault was occurred

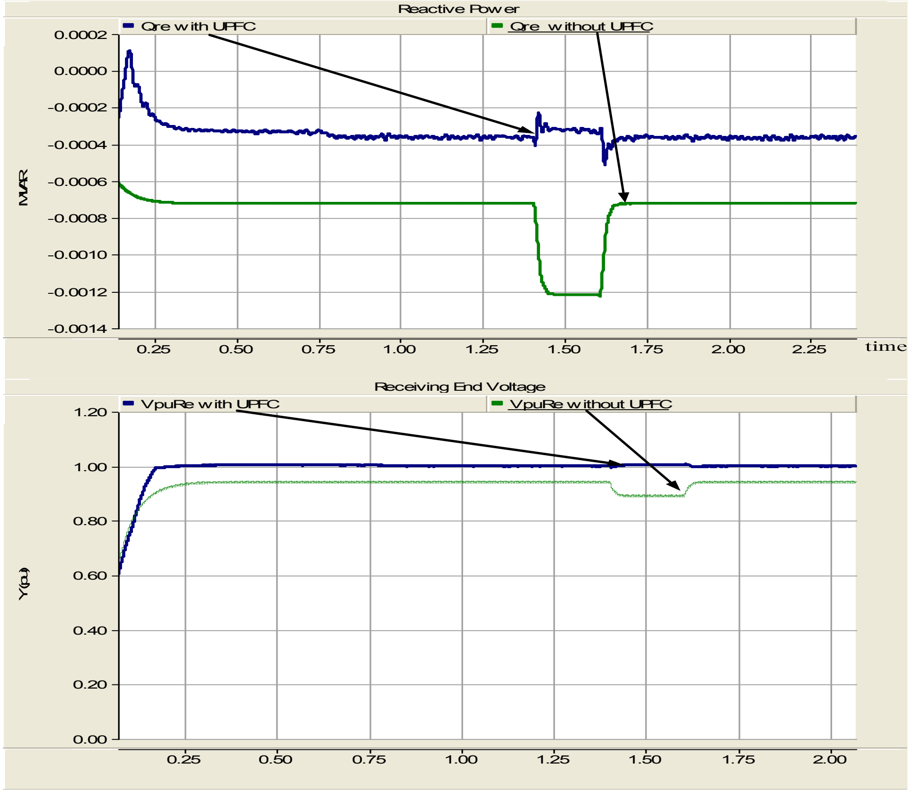


Figure 6. 11 The PID controller results when the fault was occurred

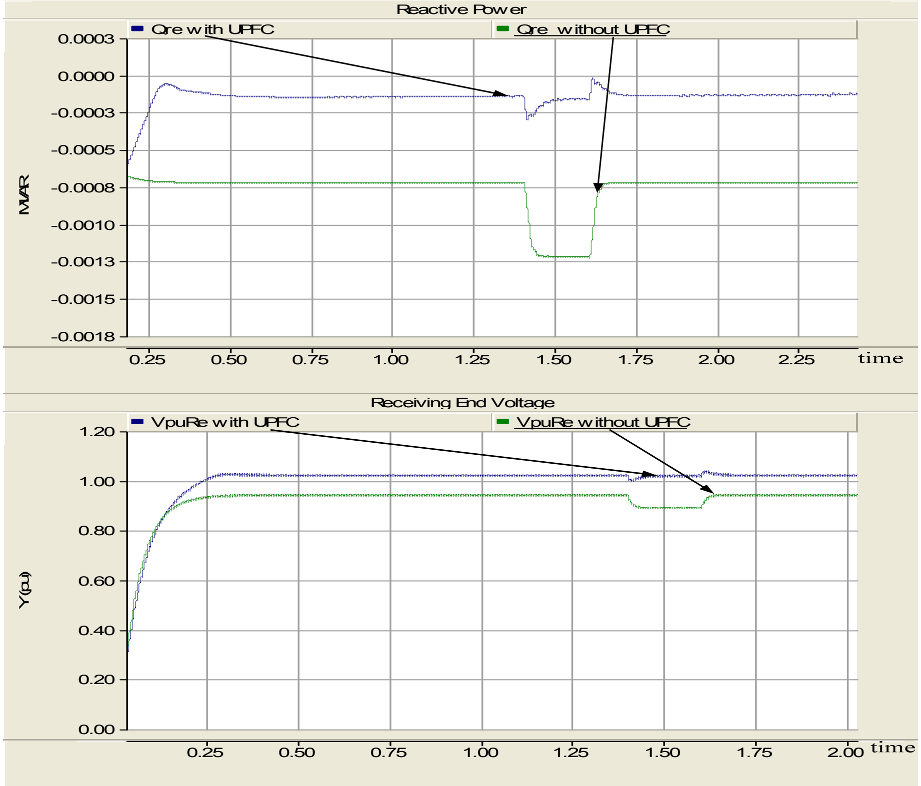


Figure 6. 12 Fuzzy controller results when the fault was applied case 4

6.4 Case 4

Two transmission lines having the same properties are used and fed by two generators in this case. The 3-phase-to-ground fault is applied in the same way as in case 3. The fault is started at 3.5 sec and its duration is 0.2. The UPFC is connected to the line 2 shown in figure 6.13.

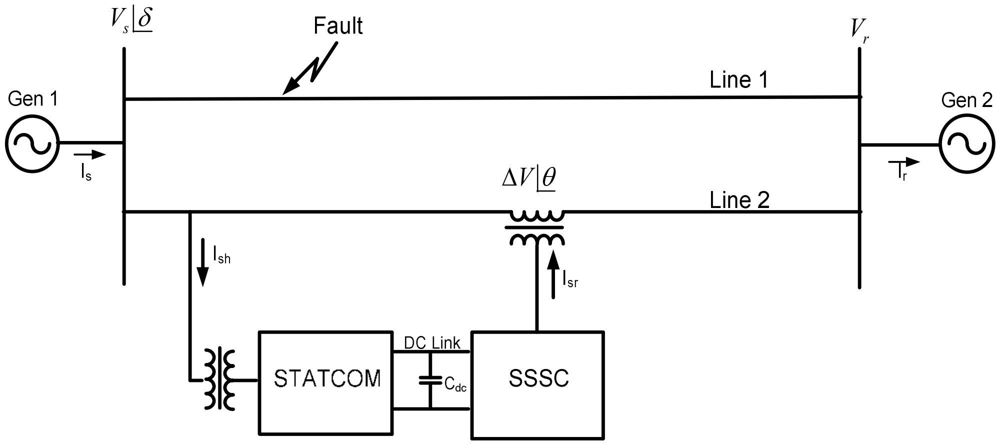


Figure 6. 13 The test system of case study 4

When the results are compared according to reactive power compensation and bus voltage control, the P and PI controllers are insufficient in the compensation and control of quantities. However, the PID and fuzzy controllers make more effective compensation of reactive power and controlling of bus voltage. The results of controllers are shown graphically in figure 6.14 to 6.17.

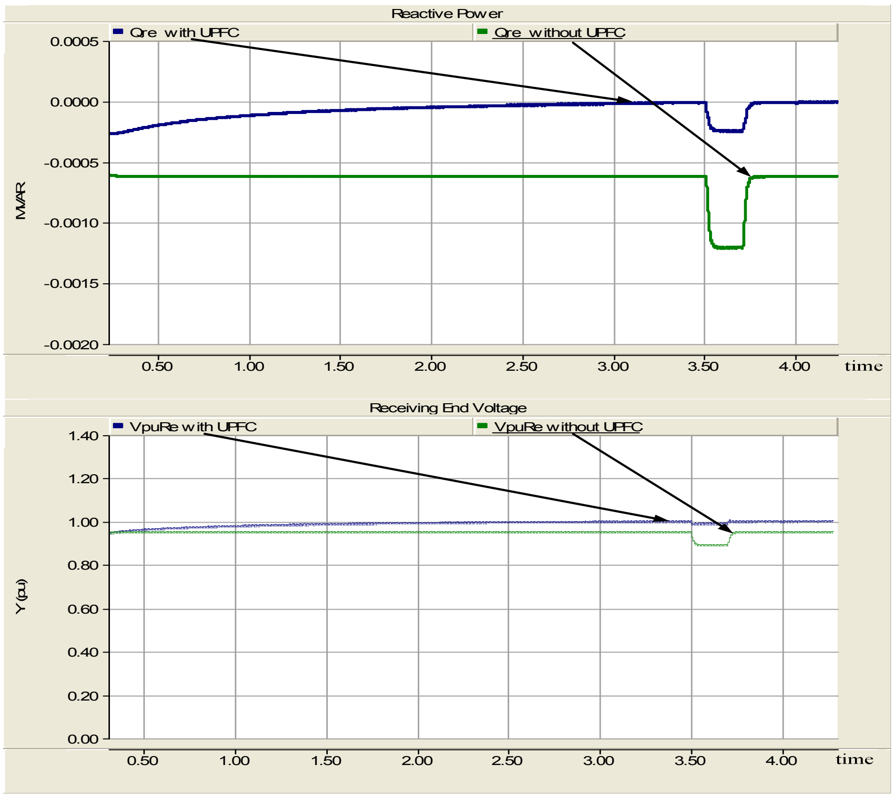


Figure 6. 14 The P controller results when the fault was occurred

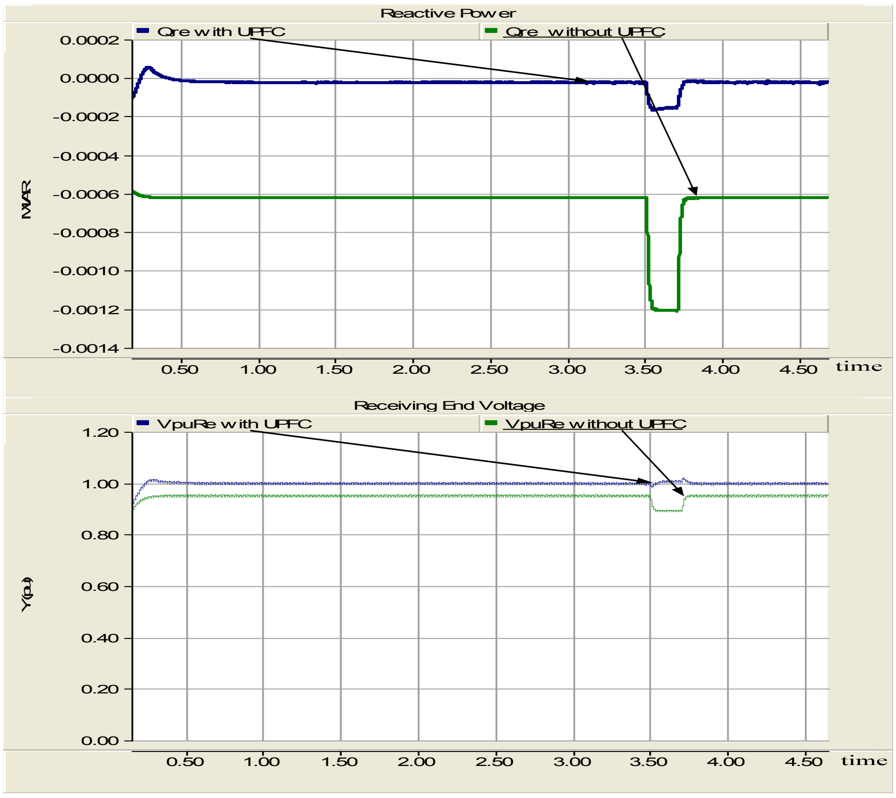


Figure 6. 15 The PI controller results when the fault was occurred

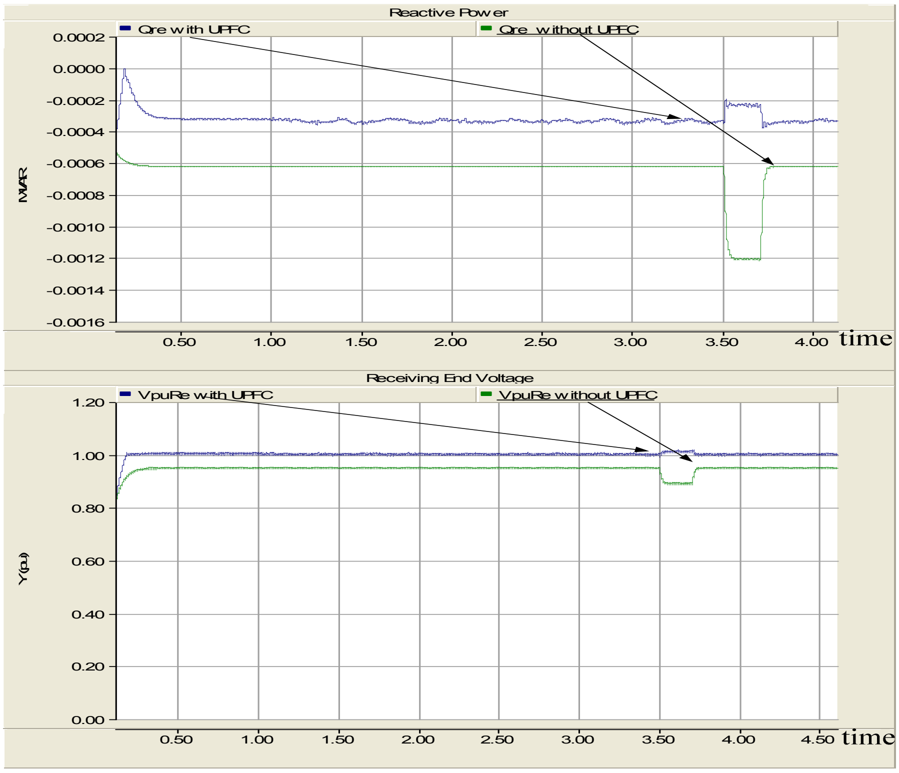


Figure 6. 16 The PID controller results when the fault was occurred

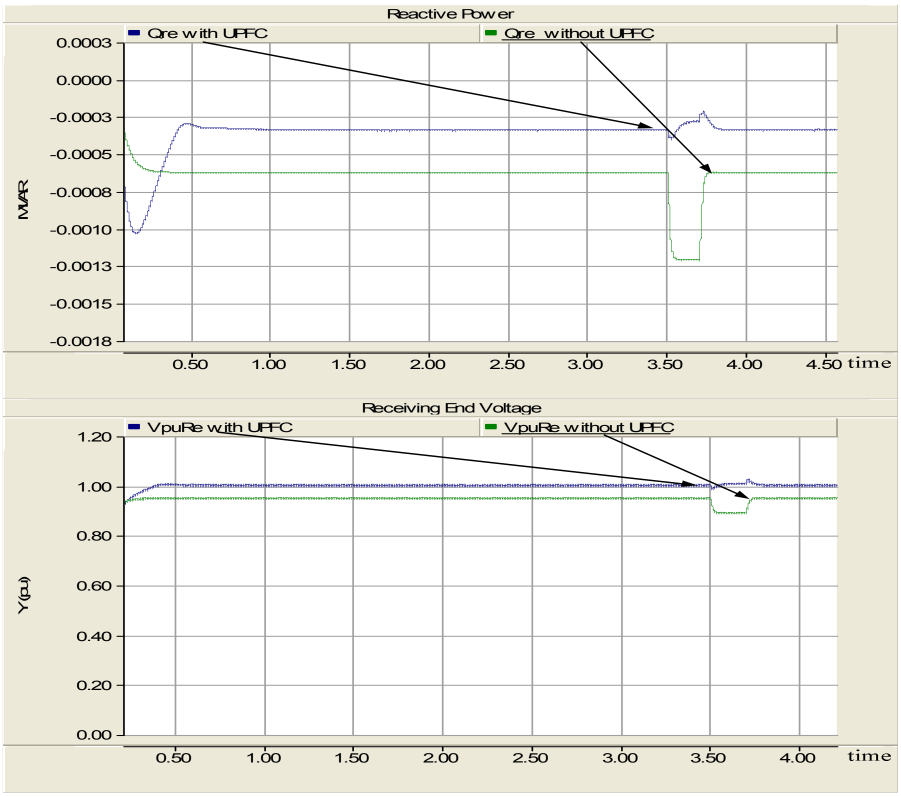


Figure 6. 17 The Fuzzy controller results when the fault was occurred

6.5 Conclusion

The performance of controllers is tested and the results are. The case studies 1 and 2 show the performance of controllers on power flow while case studies 3 and 4 show the performance of controllers when the phase-to-ground fault occurs. The P controller’s results show the effective performance neither at the bus voltage control nor at the reactive power compensation. However, other controllers have more effective performance than P controller. The fuzzy controller shows the best performance among these controllers.

7. CONCLUSIONS

This thesis deals with FACTS devices known as the Unified Power Flow Controller that is used to maintain and improve power system operation and stability. The research carried out in this thesis has focus on investigation of performance of UPFC on power flow with different controllers.

The derivation of mathematical framework of UPFC and the understanding of this basic operating principle were discussed. This framework confirmed the superior capabilities of UPFC in the power flow applications over traditional reactive power compensators.

The Power System Simulation CAD (PSCAD/EMTDC program) is used for the simulation of UPFC. This program includes device models in its library. It includes only PI controllers for the modeling of UPFC. In this thesis, the P, PID and fuzzy controllers were developed and added as a new component into PSCAD/EMTDC program library. Additionally, conventional as well as intelligent control schemes can be applied in PSCAD/EMTDC program easily. The disadvantage of the simulation packages is the simulation time. The simulation time is a function of the number of the time steps. Adding new devices and the increase in the system size enhance the simulation time leading to the quite time consuming simulations.

The comprehensive simulation cases are examined, and the results show that the proposed model and controllers are both effective and reliable. The detailed observation has been made on power system parameters, such as real and reactive power flows as well as bus voltage control in this study. Moreover, several case studies have been made in order to investigate the effects of controllers on the power flow in the power system. All the results have been fully represented by different types of graphs in order to give clear idea about the main concern. Furthermore, the main conclusions of this study can be summarized as:

The capability of UPFC on controlling the power flow is demonstrated in the case studies 1 and 2. The receiving end generator is retarded 30.0^0 from the sending end generator in the case 1. The real and reactive powers are 2.1 KW and 0.7 KVAR respectively when UPFC is not activated while the real and reactive power are 2.45

KW and 0.1 KVAR respectively when UPFC is activated in the line. According to these results, the active power is increased 28.5 %, and reactive power is decreased 85.7 % by UPFC in terms of not activated UPFC in the line. The receiving end generator is retarded by applying different phase values, and the results are listed to see the performance of the controllers on the value table. From the simulation results, the fuzzy controller shows the best performance among the other controllers.

The fault occurs in the transmission line because of the several reasons such as phase-to-ground faults. The FACTS devices are used to prevent the damage when the faults occur in the system. To see the performances of UPFC on the faults conditions, the three-phase fault is applied to the transmission line, and results are compared in terms of compensation of the reactive power and controlling the bus voltage in case studies 3 and 4.

The results show that the P controller could not compensate the reactive power and control the bus voltage. However, other controllers show good performance on these quantities. The PI and PID controllers obtain the same values while the fuzzy controller shows the best performance among these controllers.

APPENDIX A

Voltage Source Converter

The form of VSC-based designs is used to advance solutions for STATCOM, UPFC, and SSSC etc, including its structure to name a few.

The basic duty of VSC used in the FACTS is to generate a three-phase voltage utilized from the dc link capacitor such that in the series part of UPFC, it is able to operate as an AC voltage source which injects three phase voltages in series with the power system for compensation purposes. As a conventional configuration of the VSC, the six-pulse converter is used. It includes six power semiconductor switching devices (GTO, GCT, IGBT, etc) with anti-parallel-connected diode joined with heat sinks and auxiliary equipment for gating, monitoring and grading. The VSC is connected to the transmission system via a series coupling transformer and in parallel with a dc capacitor link. By means of proper control, the amplitude and phase of the injected voltage can be varied and combined with desired requirements depending on used FACTS devices. Mainly, the operation of VSC is able to provide 2 types of connections.

- *Shunt Connected VSC:* The VSC is connected to the power system via a shunt connected transformer, as in the STATCOM configuration of Figure A1. The active power and the reactive power are exchanged between the converter by changing the amplitude and the phase angle of the produced output voltage, and the AC system can be controlled in a similar manner to that of a rotating synchronous machine. The reactive power exchange bi-directionally between the VSC and the power system, and it can be adjusted by varying the amplitude of the output voltage. If the amplitude of the output voltage is increased according to the AC system voltage, the VSC generates reactive power to give the power system. If the amplitude of the output voltage is decreased according to the AC system voltage, the VSC absorbs reactive power from the power system. The real power is exchanged bi-directionally between the VSC and the power system. It can be realized by changing the phase angle between the output voltage and the AC system voltage. If the phase angle of output voltage is advanced from the AC system voltage, the VSC supplies real power to the AC power system. If the output voltage is lagged from AC system voltage, the VSC absorbs real power from the AC power system. The real power exchange is required by another VSC, battery, and dc energy storage device like a super-conducting magnet. The exchange of real and reactive power is implemented individually. The power ratings of the VSC are calculated by the product of the power system voltage and the maximum output current.

- *Series Connected VSC*: In this case, the VSC is connected to the power system via a series connected transformer, as in the SSSC configuration of Figure A1. The magnitude and the angle of the injected voltage can be controlled by changing the amplitude and the phase angle of the produced output voltages. The VSC acts as an AC voltage source, and its output voltage injects in series with the line. The current flowing through the VSC corresponds to the line current. The power ratings of the VSC are calculated by the product of the maximum injected voltage and the maximum line current. The VSC provides only reactive power to the power system, when the injected voltage is controlled via a quadrature relationship with the line current. In this situation, there is no need for energy storage device on the dc terminal. If the injected voltage is controlled in a four-quadrant manner (360 deg.) to the line current, the VSC provides both real power and reactive power to the AC power system. In this situation, another energy storage device is needed for the real power exchanged on the dc terminal.

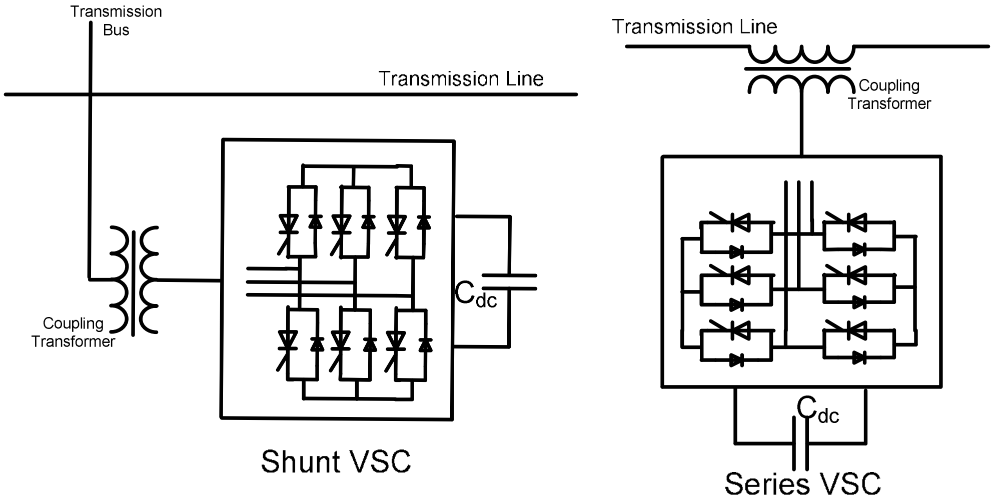


Figure A1 Basic structure of shunt and series VSCs.

APPENDIX B

Rotating (DQ) Transformation

The transformation of the three-phase stationary coordinate system into the DQ rotating coordinate system is called the DQ transformation. This transformation is made in two steps:

- The three-phase stationary coordinate system is transformed into the two-phase, so-called $\alpha\beta$ stationary coordinate system.
- The $\alpha\beta$ stationary coordinate system is transformed into rotating coordinate system, so-called dq transformation.

These steps are shown in figure B.1, B.2, B.3.

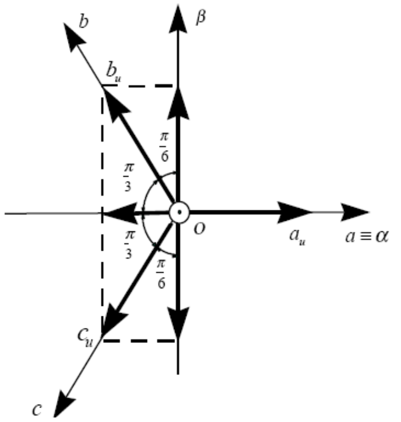
The vector representation in any n-dimensional space is completed through the product of a transpose n-dimensional vector (base) of coordinate units and a vector representation of the vector, whose elements are corresponding projections on each coordinate axis, is normalized by their unit values. The three-phase (three dimensional) space is given as vectorial in equation 1:

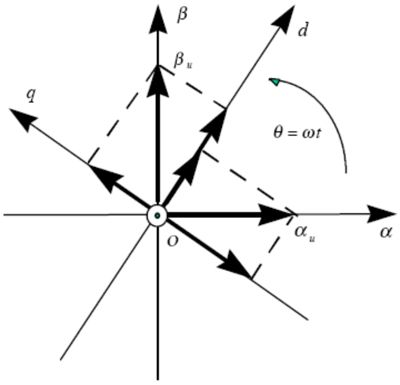
$$X_{abc} = \begin{bmatrix} a_u b_u c_u \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad \text{(B.1)}$$

The three-phase vector representation transforms to dq vector representation (zero-axis component is 0) through the transformation matrix T by assuming a balanced three-phase system ($x_{o=}0$), defined as:

$$T = \frac{2}{3}\begin{pmatrix} \cos(wt) & \cos(wt - \frac{2}{3}\pi) & \cos(wt + \frac{2}{3}\pi) \\ -\sin(wt) & -\sin(wt - \frac{2}{3}\pi) & -\sin(wt + \frac{2}{3}\pi) \end{pmatrix} \qquad \text{(B.2)}$$

In other words, the transformation from $X_{abc} = \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$ (three-phase coordinates) to $X_{dq} = \begin{bmatrix} x_d \\ x_q \end{bmatrix}$ (DQ rotating coordinates), called Park's transformation, is obtained through the multiplication the $\alpha\beta$ stationary coordinate system



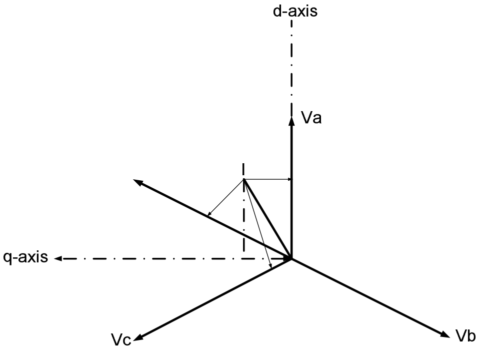


$$\left[a_u \beta_u 0_u\right] = \left[a_u b_u c_u\right]\frac{2}{3}\begin{pmatrix} 1 & 0 & \frac{1}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} \end{pmatrix}$$

$$\left[d_u q_u 0_u\right] = \left[\alpha_u \beta_u 0_u\right]\begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Figure B1 the transformation from *abc* to from $\alpha\beta$ to the $\alpha\beta$ stationary coordinate system

Figure B2 the transformation the *dq* stationary coordinate



$$\left[d_u q_u 0_u\right] = \left[a_u b_u c_u\right]\frac{2}{3}\begin{pmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & \frac{1}{2} \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & \frac{1}{2} \end{pmatrix}$$

Figure B.3 Park's transformation from three-phase to rotating dq0 coordinate system of the vector X_{abc} by the matrix T:

$$X_{dq} = TX_{abc} \tag{B.3}$$

The inverse transformation matrix (from DQ to ABC) is defined as:

$$T' = \begin{pmatrix} \cos(wt) & -\sin(wt) \\ \cos(wt - \frac{2\pi}{3}) & -\sin(wt - \frac{2\pi}{3}) \\ \cos(wt + \frac{2\pi}{3}) & -\sin(wt + \frac{2\pi}{3}) \end{pmatrix} \tag{B.5}$$

The inverse transformation is calculated as:

$$X_{abc} = T' X_{dq} \tag{B.4}$$

APPENDIX C

Pulse Width Modulation

One type of internal converter control scheme is Pulse Width Modulation (PWM). The converter can be applied as types of two-level or multilevel converters. The AC output voltage can be controlled by varying the width of the voltage pulses in these converters. There is only one turn-on and one turn-off devices in per cycle. Another approach is to have multiple-pulses per half cycle, and then vary the width of the pulses to change the amplitude of the AC voltage. The principle reason for incorporating the PWM scheme is such that the AC output voltage can easily change, and the order harmonics is reduced in lower level. The switching losses are increased with the rise of the pulse number and cannot be neglected when the PWM scheme uses.

Controlling the converter gain, and consequently the converter output voltage, is thought as the main advantage of PWM converters. There are many PWM techniques used and applied with different converter configurations. The Sinusoidal Pulse Width Modulation (SPWM) is the most popular method in PWM technique. In the SPWM, the width of each pulse is varied proportionally to the amplitude of a sinus wave, as seen in figure C.2.

C.1 Working Principle

The carrier frequency, the main frequency and the modulation index, which is an output from the main control schemes of UPFC, are used as inputs to the shunt and series pulse generator. The position of IGBTs is considered according to their connections. The diodes 1 and 4, and IGBTs 1 and 4 must be anti-parallel on one phase-leg of three-phase bridge converter. It is seen in figure C.1.

The comparison of the two types of control signals are shown in Figure C.2, one of them is main-frequency sinus wave representing one phase, and the other is

3.5 KHz frequency saw- tooth wave signal. According to these signals, the firing pulses of IGBTs are produced as follows.

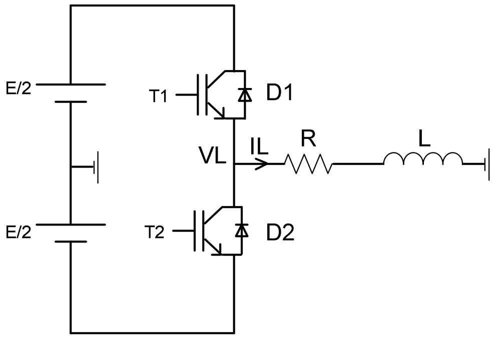


Figure C.l Simple Voltage Sourced Converter

In the crossing points of the saw-tooth wave and the corresponding phase of sinus wave, the turn-on and turn-off pulses are obtained and given to the devices. When the negative slope of the saw-tooth wave crosses the phase A of sinus wave, the turn-on pulse for device 1 and turn- off pulse for device 4 are obtained. When the positive slope of the saw-tooth wave crosses the phase A of sinus wave, the turn-off pulse for device 1 and turn-on pulse for device 4 are obtained. The pulses are wider in the middle of each half sinus wave when comparing the ends of the half sinus wave.

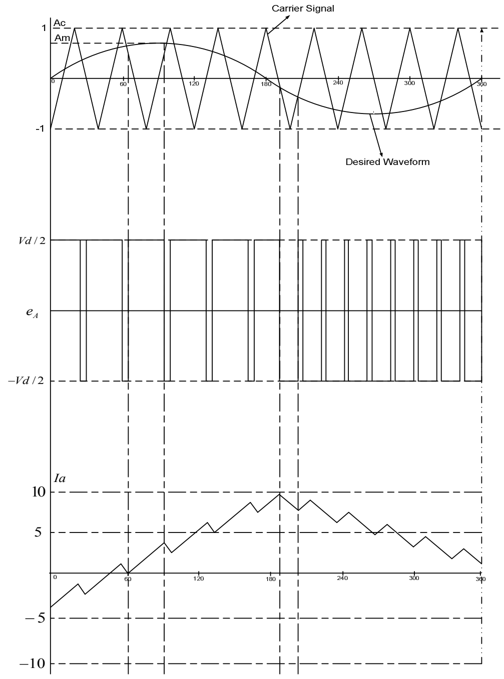


Figure C.2 Principle of Pulse with Modulation

The switches are controlled by turn-on and turn-off pulses, which correspond to the crossing points of the control waveform with the carrier waveform of corresponding phase in the six pulse voltage-sourced converter. The fundamental frequency of the output voltage (50 HZ or 60 HZ) is determined by the frequency of the carrier signal. The frequency modulation ratio m_f is the ratio between frequencies of the carrier and control waveforms, as given follow.

$$m_f = \frac{f_{carrier}}{f_{control}} \tag{C.1}$$

The magnitude of the carrier waveform is controlled from zero to its maximum value by varying the amplitude of the control waveform and the result that the pulse width can vary from 0 to 180^0. The modulation ratio m_a defines the ratio between the control and carrier waveforms:

$$m_a = \frac{d_{control}}{d_{carrier}} \tag{C.2}$$

The dc midpoint voltage for the phase A is shown figure C.2 as waveform e_A, which fluctuates between –Vdc/2 and +Vdc/2. The amplitude of the phase at fundamental frequency component to the dc midpoint voltage is m_a times Vdc/2:

$$e_a = m_a \frac{V_{dc}}{2} \tag{C.3}$$

The equations for the magnitude of the shunt and series-injected voltages are as follow, when the PWM technique is applied to the two converters:

$$Vsh = m_{sh}(V_{dc}) / 2\sqrt{2}n_{sh}V_B \tag{C.4}$$

$$Vsh = m_{se}(V_{dc}) / 2\sqrt{2}n_{se}V_B \tag{C.5}$$

The amplitude modulation index of the shunt converter control signal is m_{sh}, the amplitude modulation index of the series converter control signal is m_{se}, the shunt transformer turn ratio is n_{sh}, the series transformer turn ratio is n_{se}, the system side base voltage is V_B.

APPENDIX D

The codes used fuzzy controller in PSCAD/EMTDC program as follow:

```
    #LOCAL REAL X 9
    #LOCAL REAL M
    #LOCAL REAL ZX 7
    #LOCAL REAL N
    #LOCAL REAL EG 4
    #LOCAL REAL YE 7
    #LOCAL REAL Y 9
    #LOCAL REAL B 7
    #LOCAL REAL DGTB 49
    #LOCAL REAL K 49
    #LOCAL REAL GE
    #LOCAL REAL S
    #LOCAL REAL L 49
    N=$i1
    M=$i2
C  ERRORS
    X(1)=-1
    X(2)=-0.45
    X(3)=-0.3
    X(4)=-0.15
    X(5)=0
    X(6)=0.15
    X(7)=0.3
    X(8)=0.45
    X(9)=1
C  ERROR RATES
    Y(1)=-0.3
    Y(2)=-0.15
    Y(3)=-0.1
    Y(4)=-0.05
    Y(5)=0
    Y(6)=0.05
    Y(7)=0.1
    Y(8)=0.15
    Y(9)=0.3
C  CORRECT TABLE
    DGTB(1)=1
    DGTB(2)=1
    DGTB(3)=1
    DGTB(4)=0.8
    DGTB(5)=0.8
    DGTB(6)=0.4
    DGTB(7)=0.0
    DGTB(8)=1
    DGTB(9)=1
    DGTB(10)=0.8
    DGTB(11)=0.8
    DGTB(12)=0.4
    DGTB(13)=0
    DGTB(14)=-0.4
    DGTB(15)=1
    DGTB(16)=0.8
    DGTB(17)=0.8
    DGTB(18)=0.4
    DGTB(19)=0
    DGTB(20)=-0.4
    DGTB(21)=-0.8
    DGTB(22)=0.8
    DGTB(23)=0.8
    DGTB(24)=0.4
    DGTB(25)=0
    DGTB(26)=-0.4
    DGTB(27)=-0.8
    DGTB(28)=-0.8
    DGTB(29)=0.8
    DGTB(30)=0.4
    DGTB(31)=0
    DGTB(32)=-0.4
    DGTB(33)=-0.8
    DGTB(34)=-0.8
    DGTB(35)=-1
    DGTB(36)=0.4
    DGTB(37)=0
    DGTB(38)=-0.4
    DGTB(39)=-0.8
    DGTB(40)=-0.8
    DGTB(41)=-1
    DGTB(42)=-1
    DGTB(43)=0
    DGTB(44)=-0.4
    DGTB(45)=-0.8
    DGTB(46)=-0.8
    DGTB(47)=-1
    DGTB(48)=-1
    DGTB(49)=-1
```

```
C DETERMINATION OF
         TRAJECTORY
    EG(1)=(1/X(6)
    EG(2)=-EG(1)
    EG(3)=(1/Y(6))
    EG(4)=-EG(3)

C OUTPUT CALCULATION ACCORDING TO ERROR
     IF(N.GE.X(1).AND.N.LT.X(2)) ZX(7)=1
     IF(N.GE.X(2).AND.N.LT.X(3)) ZX(7)=EG(2)*(N-X(3))

     IF(N.GE.X(2).AND.N.LT.X(3)) ZX(6)=EG(1)*(N-X(2))
     IF(N.GE.X(3).AND.N.LT.X(4)) ZX(6)=EG(2)*(N-X(4))

     IF(N.GE.X(3).AND.N.LT.X(4)) ZX (5)=EG(1)*(N-X(3))
     IF(N.GE.X(4).AND.N.LT.X(5)) ZX(5)=EG(2)*(N-X(5))

     IF(N.GE.X(4).AND.N.LT.X(5)) ZX(4)=EG(1)*(N-X(4))
     IF(N.GE.X(5).AND.N.LT.X(6)) ZX(4)=EG(2)*(N-X(6))

     IF(N.GE.X(5).AND.N.LT.X(6)) ZX(3)=EG(1)*(N-X(5))
     IF(N.GE.X(6).AND.N.LT.X(7)) ZX(3)=EG(2)*(N-X(7))

     IF(N.GE.X(6).AND.N.LT.X(7)) ZX(2)=EG(1)*(N-X(6))
     IF(N.GE.X(7).AND.N.LT.X(8)) ZX(2)=EG(2)*(N-X(8))

     IF(N.GE.X(7).AND.N.LT.X(8)) ZX(1)=EG(1)*(N-X(7))
     IF(N.GE.X(8).AND.N.LT.X(9)) ZX(1)=1

C OUTPUT CALCULATION ACCORDING TO ERROR RATES
     IF(M.GE.Y(1).AND.M.LT.Y(2)) B(7)=1
     IF(M.GE.Y(2).AND.M.LT.Y(3)) B(7)=EG(4)*(M-Y(3))

     IF(M.GE.Y(2).AND.M.LT.Y(3)) B(6)=EG(3)*(M-Y(2))
     IF(M.GE.Y(3).AND.M.LT.Y(4)) B(6)=EG(4)*(M-Y(4))

     IF(M.GE.Y(3).AND.M.LT.Y(4)) B(5)=EG(3)*(M-Y(3))
     IF(M.GE.Y(4).AND.M.LT.Y(5)) B(5)=EG(4)*(M-Y(5))

     IF(M.GE.Y(4).AND.M.LT.Y(5)) B(4)=EG(3)*(M-Y(4))
     IF(M.GE.Y(5).AND.M.LT.Y(6)) B(4)=EG(4)*(M-Y(6))

     IF(M.GE.Y(5).AND.M.LT.Y(6)) B(3)=EG(3)*(M-Y(5))
     IF(M.GE.Y(6).AND.M.LT.Y(7)) B(3)=EG(4)*(M-Y(7))

     IF(M.GE.Y(6).AND.M.LT.Y(7)) B(2)=EG(3)*(M-Y(6))
```

```
     IF(M.GE.Y(7).AND.M.LT.Y(8)) B(2)=EG(4)*(M-Y(8))
     IF(M.GE.Y(7).AND.M.LT.Y(8)) B(1)=EG(3)*(M-Y(7))
     IF(M.GE.Y(8).AND.M.LT.Y(9)) B(1)=1

C MINIMIZATION OF TWO INPUTS
     DO I=1,7,1
     K(I)= MIN (ZX(1),B(I))
     END DO
     DO  I=1,7,1
     K(I+7)= MIN (ZX(2),B(I))
     END DO
     DO  I=1,7,1
     K(I+14)= MIN (ZX(3),B(I))
     END DO
     DO  I=1,7,1
     K(I+21)= MIN (ZX(4),B(I))
     END DO
     DO  I=1,7,1
     K(I+28)= MIN (ZX(5),B(I))
     END DO
     DO  I=1,7,1
     K(I+35)= MIN (ZX(6),B(I))
     END DO
     DO I=1,7,1
     K(I+42)= MIN (ZX(7),B(I))
     END DO
     S=0
     GE=0
     DO I=1,49,1
     L(I)= DGTB(I)*K(I)
     END DO
     DO  I=1,49,1
     S=S+L(I)
     GE=GE+ K(I)
     END DO
     $o13=S/GE
```

APPENDIX E

The technical details of sending end and receiving end generators:

Sending End Generator

Based MVA (3-phase) : 0.01 [MVA]
Base Voltage (L-L, RMS) : 0.380 [kV]
Base Frequency : 50.0 [Hz]
Phase : 0.0 [°]

Receiving End Generator

Based MVA (3-phase) : 0.01 [MVA]
Base Voltage (L-L, RMS) : 0.380 [kV]
Base Frequency : 50.0 [Hz]
Phase : 0.0 [°]

The technical details of shunt converter transformers:

Based MVA (3-phase) :0.003 [MVA]
Winding #1 Voltage (L-L, RMS) :0.380 [kV]
Winding #2 Voltage (L-L, RMS) :0.040 [kV]
Base Operation Frequency :50.0 [Hz]

The technical details of series converter transformers:

Based MVA (3-phase) :0.003 [MVA]
Winding #1 Voltage (L-L, RMS) :0.110 [kV]
Winding #2 Voltage (L-L, RMS) :0.110 [kV]
Base Operation Frequency :50.0 [Hz]

The technical details of generators used in case studies:

Sending End Generator

Based MVA (3-phase) : 0.01 [MVA]
Base Voltage (L-L, RMS) : 0.380 [kV]
Base Frequency : 50.0 [Hz]
Phase : 0.0 [°]

Receiving End Generator

Based MVA (3-phase) : 0.01 [MVA]
Base Voltage (L-L, RMS) : 0.380 [kV]
Base Frequency : 50.0 [Hz]
Phase : -30.0 [°]

REFERENCES

AIHONG T., SHIJIE C., 2005. “**Upfc Control Algorithm and Implementation Scheme in Laboratory**”, Digital Object Identifier 10.1109/Tdc...1546798.

AMBRIZ-PEREZ, H., ACHA, E., FUERTE-ESQUIVEL, C.R., DE LA TORRE, A., 1998. “**Incorporation of a UPFC Model in an Optimal Power Flow Using Newton's Method”,** Volume 145, Issue 3, Page(S):336–344.

ELDAMATY A.A., FARIED S.O., ABORESHAID S., 2005. “**Damping Power System Oscillations Using a Fuzzy Logic Based Unified Power Flow Controller**”, Page(S):1950-1953 Digital Object Identifier 10.1109/Ccece.2005.1557364.

FUERTE-ESQUIVEL, C.R., ACHA, E., 1997. “**Unified Power Flow Controller: a Critical Comparison of Newton-Raphson Upfc Algorithms in Power Flow Studies”,** Volume 144, Issue 5, Page(S):437–444.

FUJITA H., AKAGI, H., WATANABE, Y., 2006. “**Dynamic Control and Performance of a Unified Power Flow Controller for Stabilizing an AC Transmission System**”, Volume 21, Issue 4, Page(S):1013-1020 Digital Object Identifier 10.1109/Tpel.2006.876845.

GAO, Y., ZHANG, Y., KAN,Y., 2005. “**Control Design and Analysis of Upfc Shunt Converter”,** 14-17 Page(S):536-540 Digital Object Identifier 10.1109/Icit.2005.1600696.

GREEN, A.W., BOYS, J.T., 1989. “**Hysteresis Current-Forced Three-Phase Voltage-Sourced Reversible Rectifier”,** Volume 136, Issue 3, Page(S):113-120.

GYUGYI, L., 1992. “**Unified Power-Flow Control Concept for Flexible AC Transmission Systems”,** Volume 139, Issue 4, Page(S):323 – 331.

HINGORANI, N.G., 1993. “**Flexible AC transmission”,** Volume 30, Issue 4, Page(s):40 - 45 Digital Object Identifier 10.1109/6.206621

HOSSEINI, S.H., AJAMI, A., 2004. “**Voltage Regulation and Transient Stability Enhancement of a Radial AC Transmission System Using Upfc**”, Volume

2, 2-6 Page(S):1150-1154 Vol. 2 Digital Object Identifier 10.1109/Iecon.2004.1431737.

KALYANI, R.P., VENAYAGAMOORTHY, G.K., CROW, M., 2003. "**Neuroidentification of System Parameters for The Shunt & Series Branch Control of Upfc**", Volume 4, 13-17 Page(S): Digital Object Identifier 10.1109/Pes.2003.1271018.

KANNAN, S., JAYARAM, S., SALAMA, M.M.A., 2004 "**Real and Reactive Power Coordination for a Unified Power Flow Controller**", Volume 19, Issue 3, Page(S):1454-1461 Digital Object Identifier 10.1109/Tpwrs.2004.831690.

LIU, L.., ZHU, PE.., KANG,Y., CHEN, J., 2005. "**Design and Dynamic Performance Analysis of a Unified Power Flow Controller**", Page(S):6 Pp. Digital Object Identifier 10.1109/Iecon 2005.1569093.

LO, K.L., MA, T.T., TRECAT, J., CRAPPE, M., 1998. "**A Novel Power Flow Control Concept Using Ann Based Multiple UPFCs Scheme",** Volume 2, 3-5 1998 Page(S):570-575 Vol.2 Digital Object Identifier 10.1109/Empd.1998.702748.

LU, B., BOON OOI, T., 1997. "**Unified Power Flow Controller (Upfc) Under Nonlinear Control",** Volume 1, 9-14 Page(S):197-201 Vol.1 Digital Object Identifier 10.1109/Iecon.1997.671046.

MA, T.T., LO, K.L., 2000. "**Nonlinear Power System Damping Control Strategies for The Unified Power Flow Controller (Upfc)**", Volume 2, 4-7 Page(S):673-678 Vol.2 Digital Object Identifier 10.1109/Icpst.2000.897103.

MENG, Z.J., SO, P.L., 2000. "**A Current Injection Upfc Model for Enhancing Power System Dynamic Performance",** Volume 2, 23-27 Page(S):1544-1549 Vol.2 Digital Object Identifier 10.1109/Pesw.2000.850212.

MISHRA, S., 2006. "**Neural-Network-Based Adaptive Upfc for Improving Transient Stability Performance of Power System**", Volume 17, Issue 2, Page(S):461-470 Digital Object Identifier 10.1109/Tnn.2006.871706.

MOK, T.K., NI, Y., WU, F.F., 2000. "**Design of Fuzzy Damping Controller of Upfc Through Genetic Algorithm**", Volume 3, 16-20 Page(S):1889 - 1894 Vol. 3 Digital Object Identifier 10.1109/Pess.2000.868822.

NABAVI-NIAKI, A., IRAVANI, M.R., 1996. "**Steady-State and Dynamic Models of Unified Power Flow Controller (Upfc) for Power System Studies**", Volume 11, Issue 4, Page(S):1937-1943 Digital Object Identifier 10.1109/59.544667.

NGUYEN, P.T., SAHA, T.K., 2004. "**Dynamic Voltage Restorer Against Balanced and Unbalanced Voltage Sags: Modeling and Simulation**", 6-10 Page(S):639-644 Vol.1 Digital Object Identifier 10.1109/Pes.2004.1372883.

ORIZONDO, R., ALVES, R., 2006. "**Damping Power System Oscillations Using a Fuzzy Logic Based Unified Power Flow Controller**", Page(S):1-7 Digital Object Identifier 10.1109/Tdcla.2006.311458.

PADIYAR, K.R., KULKARNI, A.M., 1998. "**Control Design and Simulation of Unified Power Flow Controller**", Volume 13, Issue 4, Page(S):1348-1354 Digital Object Identifier 10.1109/61.714507.

PAPIC, I., ZUNKO, P., POVH, D., WEINHOLD,M., 1997 "**Basic Control of Unified Power Flow Controller**", Volume 12, Issue 4, Page(S):1734-1739 Digital Object Identifier 10.1109/59.627884.

QING, Y., NORUM, L., UNDELAND, T., ROUND, S., 1996. "**Investigation of Dynamic Controllers for a Unified Power Flow Controller**", Volume 3, 5-10 Page(S):1764-1769 Vol.3 Digital Object Identifier 10.1109/Iecon.1996.570729.

SAYED M, A., INAYOSHI, N., TAKESHITA T., UEDA, F., 2007. "**Line Loss Minimum Control of Loop Distribution Systems Using Upfc",** 2-5Page(S):991-996DigitalObjectIdentifier0.1109/Pccon.2007.373087.

SCHAUDER, C., MEHTA, H., 1993. "**Vector Analysis and Control of Advanced Static VAR Compensators**", Volume 140, Issue 4, Page(S):299–306.

SCHAUDER, C.D., GYUGYI L., LUND, HAMAI, M.R., RIETMAN, D.M., RIETMAN, T.R., TORGERSON, D.R., EDRIS, A., 1998. "**Operation of the Unified Power Flow Controller (Upfc) Under Practical Constraints",** Volume 13, Issue 2, Page(S):630-639 Digital Object Identifier 10.1109/61.660949

SEN, KALYAN K., STACEY, ERIC J., 1998. "**Upfc - Unified Power Flow Controller: Theory, Modeling, and Applications**", IEEE Transactions on Power Delivery, Vol. 13, No. 4.

SMITH, K.S., RAN, L., PENMAN, J., 1997. "**Dynamic Modeling of a Unified Power Flow Controller**", Volume 144, Issue 1, Page(S):7-12.

SON, K.M., LASSETER, R.H., 2004. "**A Newton-Type Current Injection Model of Upfc For Studying Low-Frequency Oscillations",** Volume 19, Issue 2, Page(S):694 - 701 Digital Object Identifier 10.1109/Tpwrd.2003.822543.

SONG, YONG H., JONS, ALLAN T., 1999. "**Flexible AC Transmission Systems (FACTS)**", IEE Power and Energy Series 30.

SUTANTO, D., SNIDER, L.A., MOK, K.L., 2000. "**Hysteresis Control Over Upfc",** Volume 2, 30 -1 Page(S):37 -379 Vol.2.

UZUNOVIC, E., , CANIZARES, CLAUDIO A., REEVE, J., 1999. "**Emtp Studies of Upfc Power Oscillation Damping**" ,North American Power Symposium (Naps), San Luis Obispo, California,

VENAYAGAMOORTHY, G.K., KALYANI, R.P., 2005, "**Two Separate Continually Online-Trained Neurocontrollers for a Unified Power Flow Controller**", Volume 41, Issue4, Page(S):906-916Digital Object Identifier 10.1109/Tia.2005.851571.

WANG, H.F., 1999. "**Applications of Modeling Upfc into Multi-Machine Power Systems**", Volume 146, Issue 3, Page(S):306-312 Digital Object Identifier 10.1049/Ip-Gtd: 19990170.

XU, BEI., ABUR A., 2004. "**State Estimation of Systems With Upfcs Using The Interior Point Method**", Volume 19, Issue 3, Page(S):1635-1641 Digital Object Identifier 10.1109/Tpwrs.2004.831703.

YONGGAO, Z., LIMING, L., PENGCHENG, Z., XIAOYUAN, L., YONG, K., YANLI, G., 2005. "**Double Closed Loop Control and Analysis for Shunt Inverter of Upfc**", Volume 2, 27-29 Page(S):1118-1123 Vol. 2.

ZHOU, X.Y., WANG, H.F., AGGARWAL, R.K., 2004. "**Detailed Modeling and Simulation of Upfc Using Emtp**", Volume 1, 6-8 Page(S):256 - 260 Vol. 1.

ZHU, P., LIU, L., LIU, X., KANG,Y., CHEN, J., 2005. "**Analysis and Comparison of Two Control Strategies for Upfc**", Digital Object Identifier 10.1109/Tdc. 1546754.

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I was born in Adana, Turkey, in 1978. I completed the high school education in Adana. I received the B.S degree in Electrical and Electronics Engineering Department from İnönü University, Malatya, Turkey in 2002. After completion my B.S. training, I finished MSc degree in the Institute Of Natural and Applied Science as secondary education of Mathematics (Non Thesis) program in 2004. I completed the duty of army in 2005. I have started second MSc degree in the department of Electrical and Electronics Engineering in Çukurova University and have been working there as research assistant since 2005.

My areas of interested include the modeling and analysis of the power systems, power electronics, FACTS devices and power quality.

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