# STABILITY IMPROVEMENT OF POWER SYSTEM USING UPFC

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF

**Master of Technology**
**in**
**Power Control and Drives**

By

**JYOTSHNAMAYEE PRADHAN**

**Department of Electrical Engineering**
**National Institute of Technology**
**Rourkela**
2007

# STABILITY IMPROVEMENT OF POWER SYSTEM USING UPFC

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF

**Master of Technology**
**in**
**Power Control and Drives**

**By**

**JYOTSHNAMAYEE PRADHAN**

Under the Guidance of

**Prof. B. D. Subudhi**

**Department of Electrical Engineering**
**National Institute of Technology**
**Rourkela**
2007

## National Institute Of Technology
## Rourkela

# CERTIFICATE

This is to certify that the thesis entitled, **"Stability Improvement of Power System using UPFC"** submitted by Ms. **Jyotshnamayee Pradhan** in partial fulfillment of the requirements for the award of Master of Technology Degree in **Electrical Engineering** with specialization in **"Power control and Drives"** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by her under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date:

**Prof. B.D. Subudhi**
Dept. of Electrical Engg.
National Institute of Technology
Rourkela-769008

# ACKNOWLEDGEMENTS


This project is by far the most significant accomplishment in my life and it would be impossible without people who supported me and believed in me.

I would like to extend my gratitude and my sincere thanks to my honorable, esteemed supervisor **Prof. B.D. Subudhi,** Department of Electrical Engineering. He is not only a great lecturer with deep vision but also most importantly a kind person. I sincerely thank for his exemplary guidance and encouragement. His trust and support inspired me in the most important moments of making right decisions and I am glad to work with him.

I would like to take this privilege to express my deep sense of gratitude to **Debasish Jena** for his valuable help and inspiring guidance that facilitated me to carry out this work satisfactorily. I sincerely thank for his exemplary guidance and encouragement. I thank him from the bottom of my heart.

I would like to thank **Asst Prof. B. K. Panigrahi** for helping me a lot during the thesis period. He has been great sources of inspiration to me.

I would like to thank all my friends and especially TSP friends for all the thoughtful and mind stimulating discussions we had, which prompted us to think beyond the obvious.

I would like to thank all those who made my stay in Rourkela an unforgettable and rewarding experience.

Last but not least I would like to thank my parents, who taught me the value of hard work by their own example. They rendered me enormous support during the whole tenure of my stay in NIT Rourkela.

***Jyotshnamayee Pradhan***

# CONTENTS

# ABSTRACT

Occurrence of a fault in a power system causes transients. To stabilize the system, Power System Stabilizer (PSS) and Automatic Voltage Regulator (AVR) are used. Load flow analysis is done to analyze the transients introduced in the system due to the occurrence of faults. The Flexible Alternating Current Transmission (FACTS) devices such as UPFC are becoming important in suppressing power system oscillations and improving system damping. The UPFC is a solid-state device, which can be used to control the active and reactive power. This thesis considers a typical three-machine nine-bus system as a case study for investigating the performance of UPFC is achieving stability. By using a UPFC the oscillation introduced by the faults, the rotor angle and speed deviations can be damped out quickly than a system without a UPFC. The effectiveness of UPFC in suppressing power system oscillation is investigated by analyzing their oscillation in rotor angle and change in speed occurred in the three machine system considered in this work. A proportional integral (PI) controller has been employed for the UPFC. It is also shown that a UPFC can control independently the real and reactive power flow in a transmission line.

A MATLAB simulation has been carried out to demonstrate the performance of the UPFC in achieving transient stability of the three-machine nine-bus system.

# LIST OF FIGURES

# LIST OF TABLES

# Chapter 1

# INTRODUCTION

# INTRODUCTION

## 1.1 BACKGROUND

The classical model of a multi machine may be used to study the stability of a power system for a period of time during which the system dynamic response is dependent largely on the kinetic energy in the rotating masses. The classical three-machine nine-bus system[1] is the simplest model used in studies of power system dynamics and requires of minimum amounts of data. Hence such studies can be connected in a relatively short time under minimum cost. Among various method of load flow calculation Newton raphson method[10-14] is chosen for calculation of load flow study.

If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable. If the system is not stable, it is considered unstable. This primitive definition of stability requires that the system oscillations should be damped. This condition is sometimes called asymptotic stability and means that the system contains inherent forces that tend to reduce oscillation.

The continuing rapid development of high-power semiconductor technology now makes it possible to control electrical power systems by means of power electronic devices.[15] These devices constitute an emerging technology called FACTS (flexible alternating current transmission systems). FACTS technology has a number of benefits, such as greater power flow control, increased secure loading of existing transmission circuits, damping of power system oscillations, less environmental impact and, potentially, less cost than most alternative techniques of transmission system reinforcement [11].

The UPFC is the most versatile of the FACTS devices. It cannot only perform the functions of the static synchronous compensator (STATCOM), thyristor switched capacitor (TSC) thyristor controlled reactor (TCR), and the phase angle regulator but also provides additional flexibility by combining some of the functions of the above controllers[17]. The main function of the UPFC is to control the flow of real and reactive power by injection of a voltage in series with the transmission line. Both the magnitude and the phase angle of the voltage can be varied independently. Real and reactive power flow control can allow for power flow in prescribed routes, loading of transmission lines closer to their thermal limits and can be utilized for improving transient and small signal stability of the power system. The schematic of the UPFC is shown in Fig.1.1.

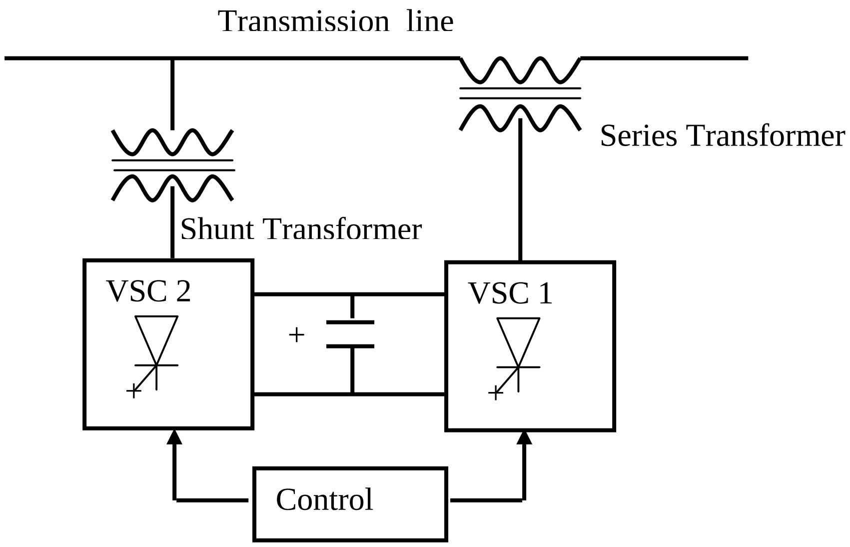


Fig.1.1. Schematic diagram of UPFC

The UPFC consists of two branches. The series branch consists of a voltage source converter, which injects a voltage in series through a transformer. The inverter at the input end of the UPFC is connected in shunt to the AC power system and the inverter at the input end of the UPFC is connected in series with the AC transmission circuit. Since the series branch of the UPFC can inject a voltage with variable magnitude and phase angle it can exchange real power with the transmission line. However the UPFC as a whole cannot supply or absorb real power in steady state (except for the power drawn to compensate for the losses) unless it has a power source at its DC terminals.

The UPFC can control the transmission real power, at its series-connected output end, while independently providing reactive power support to the transmission line at its shunt-connected input end. Furthermore, the UPFC can independently control real and reactive power flow along the transmission line at its output end, while providing reactive power support to the transmission line at its input end. It has been shown [ 2-4] that it is possible to independently control real and reactive power flow at the UPFC input circuit by regulating the DC-link capacitor voltage and varying both the phase angle and the modulation index of the input inverter. The DC-link capacitor voltage ($V_{dc}$) is unregulated.

The main parameter of a power system i.e. line impedance ($X_L$), terminal voltage ($V_t$) and rotor angle ($\delta$). The effectiveness of UPFC is analyzed by analyzing, damping of the oscillation of rotor angle ($\delta$) and change in angular speed (dw) is analyzed in the three machine of the 3-machine nine bus system.

The control of an AC power system in real time is involved because power flow is a function of the transmission line impedance, the magnitude of the sending and receiving end voltages, and the phase angle between these voltages. Years ago, electric power systems were relatively simple and were designed to be self-sufficient; power exportation and importation were rare. Furthermore, it was generally understood that AC transmission systems could not be controlled fast enough to handle dynamic system conditions. The sustainability of a power system is the most important point. Therefore the important point of a power system is the transient stability analysis of a system. To analyze the transient stability of a system a common three machine nine bus system is taken and its power flow study is done by Newton Raphson method among the various load flow calculation method such as Newton Raphson, Runge Kutta method, Decoupled method.[18] By load flow analysis the Transient behavior of the multi machine system is analyzed. The behavior of the rotor angle ($\delta$) and change in angular speed is analyzed without UPFC. Transmission systems were designed with fixed or mechanically-switched series and shunt reactive compensations, together with voltage regulating and phase-shifting transformer tap-changers, to optimize line impedance, minimize voltage variation, and control power flow under steady-state or slowly changing load conditions[21-25]. The dynamic system problems were usually handled by over design; transmission systems were designed with generous stability margins to recover from anticipated operating contingencies caused by faults, line and generator outages, and equipment failures. All these resulted in the (often considerable) under utilization of transmission systems.

## 1.2 LITERATURE RIVIEW

In recent years, energy, environment, right-of-way, and cost problems have delayed the construction of both generation facilities and new transmission lines, while the demand for electric power has continued to grow. This situation has necessitated a review of the traditional power system concepts and practices to achieve greater operating flexibility and better utilization of existing power systems[7-10].

During the last two decades, major, if not revolutionary, advances have been made in high-power semiconductor device and control technologies[28,29,34,35] These technologies have been instrumental in the broad application of high voltage DC transmission and power system inertia schemes, and they have already made a significant impact on AC transmission via the increasing use of thyristor controlled static VAr compensators (SVCs).

Static VAr compensators control only one of the three important parameters (voltage, impedance, phase angle) determining the power flow in AC power systems: the amplitude of the voltage at selected terminals of the transmission line. Theoretical considerations and recent system studies [1] indicate that high utilization of a complex, interconnected AC power system, meeting the desired objectives for availability and operating flexibility, may also require the real-time control of the line impedance and the phase angle. Hingorani [17] proposed the concept of flexible AC transmission systems or FACTS, which includes the use of high-power electronics, advanced control centers, and communication links, to increase the usable power transmission capacity to its thermal limit. Within the framework of FACTS, and other efforts with similar objectives, the development of thyristor-controlled series compensators for line impedance control, thyristor-controlled tap-changing transformers for phase angle control, and other thyristor-controlled devices for dynamic 'brakes' and over voltage suppressors has already been started [3, 4] or is expected to start in the near future.

Although present static VAr compensators and other thyristor-controlled equipments developed for power flow control (i.e., series compensators and phase shifters) can have the necessary speed for real-time control, they are rather large, custom-designed and fabricated systems of substantial cost, requiring considerable size facility with significant labour installation[24-29]. For these reasons, it is unlikely that they will be able to provide the long-term, volume-production based economic solution for flexible AC transmission systems. It has long been realized that an all solid-state or advanced, static VAr compensator, which is the true equivalent of an ideal synchronous condenser, is technically feasible [5-8] and, with the use of gate turn-off (GTO) thyristors[10,31], is economically viable [17]**.** The extension of this approach to controllable series compensation and phase shifting has been recently proposed [5].But the other thyrstorised FACT devices provide only specific control[20-26]. So UPFC is the more versatile FACT device, which can provide various types of control such as voltage compensation, phase shifting, real and reactive power compensation. So by using the UPFC the power system transient stability is enhanced by placing it in the bus of the power system. Which enhance the power carring capability and Transient stability of the power system approach of power transmission control promises simplified system design, reduction in equipment size and installation labour, improvements in performance, and significant reduction in capital cost, fuelled by advances in power semiconductor technology.

## 1.3 MOTIVATION OF THE PRESENT WORK

Transient stability of a transmission is a major area of research from several decades. Transient stability restores the system after fault clearance. Any unbalance between the generation and load initiates a transients that causes the rotors of the synchronous machines to “swing” because net accelerating torques are exerted on these rotors. If these net torques are sufficiently large to cause some of the rotors to swing far enough so that one or more machines “slip a pole” and synchronism is lost. So the calculation of transient stability should be needed. A system load flow analysis is required for it .The transient stability needs to be enhanced to optimize the load ability of a system, where the system can be loaded closer to its thermal limits. UPFC is a device which gives both the series and shunt compensation. It also enhances the real and reactive power capacity of the system.

## 1.4 PROBLEM STATEMENT

Occurrence of fault may lead to instability in a system or the machine fall out of synchronism. Load flow study should be done to analyze the transient stability of the power system. If the system can’t sustain till the fault is cleared then the fault instabilise the whole system. If the oscillation in rotor angle around the final position go on increasing and the change in angular speed during transient condition go on increasing then system never come to its final position. The unbalanced condition or transient condition may leads to instability where the machines in the power system fall out of synchronism. Calculation of load flow equation by Newton Raphson method, rungee kutta method, decoupled method gives the rotor angle and initial condition.

To optimize the cost and optimum use of transmission line compensation is needed, which can either, compensate the voltage, phase shift, or both the increase of voltage and phase shift, and real and reactive power enhancement. Before the introduction of static power electronics device, fixed capacitor, inductor etc.are used for compensation over which control could not be done. So after introduction of FACT devices give a control on the compensation. FACT devices like STATCOM, SVC etc.are only give the shunt compensation .So some controller should need to be used which can give both series and shunt compensation, and increase its transient stability by which the transmission line loading can be closer to their thermal limits.

## **1.5** THESIS ORGNISATION

Chapter 2 describes of the model of synchronous machine, Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS). A review on UPFC is discussed in chapter 3. Control strategy of UPFC in chapter 4.A discussion on three machine nine bus system is given in chapter 5.The load flow analysis of three machine nine bus system and simulation result are given in chapter 6.At the end conclusions and scope of future work is given in chapter 7 .

# Chapter 2

# MODELLING OF SYNCHRONOUS MACHINE

# MODELLING OF SYNCHRONOUS MACHINE, AVR AND PSS

## 2.1 MATHEMATICAL MODEL OF SYNCHRONOUS MACHINE

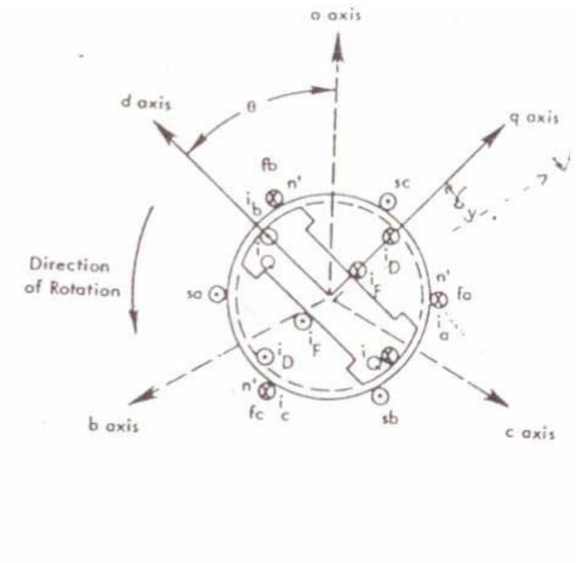


Fig.2.1 Pictorial Representation of a Synchronous Machine

A great simplification in the mathematical description of the synchronous machine is obtained if certain transformation of variable is performed. The transformation used is usually called Park's transformation. It defines a new setoff stator variable such as currents, voltages, or flux linkages in terms f the actual winding variables. The new quantities are obtained fro the projection of the actual variables on three axes; one along the direct axis of the rotor field winding, called the direct axis; a second along the neutral axis of field winding, called the quadrature axis; and the third on a stationary axis. Park's transformation[1,21,31] is developed mathematically as follows:

We define the d axis of the rotor at some instant of time to be an angle $\theta$ rad with respect to a fixed reference position, as shown un Fig.2.1.Let the stator phase currents $i_a$, $i_b$ and $i_c$ be the currents leaving the generator terminals. If we "project " these currents along the d and q axes of the rotor, we get the relations

$$i_{qaxis} = (2/3)\left[i_a \sin\theta + i_b \sin(\theta - 2\pi/3) + i_c \sin(\theta + 2\pi/3)\right] \quad (2.1)$$

$$i_{daxis} = (2/3)[i_a \cos\theta + i_b \sin\cos(\theta - 2\pi/3) + i_c \cos(\theta + 2\pi/3)] \tag{2.2}$$

We note that for convenience the axis of phase *a* was chosen to be the reference position, otherwise some angle of displacement between phase *a* and arbitrary reference will appear in all the above terms.

The effects of Park's transformation is simply to transformation is simply to transform all stator quantities from phases a, b, and c into new variables the frame of reference of which moves with the rotor. We should remember, however, that if we have three variables $\mathbf{i_a}$ ,$\mathbf{i_b}$, and $\mathbf{i_c}$, we need three new variables. Park's transformation uses two of the new variables as the d and q axis components. The third variables are stationary currents, which is proportional to the zero-sequence current. A multiplier is used to simplify the numerical calculations. Thus by definition

$$i_{0dq} = P i_{abc} \tag{2.3}$$

where we define the current vectors

$$i_{0dq} = \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} \qquad i_{abc} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2.4}$$

and where the Park's transformation **P** is defined as

$$P = \sqrt{2/3}\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \end{bmatrix} \tag{2.5}$$

The main field-winding flux is along the direction of the *d* axis of the rotor. It produces the EMF that lags this flux by $90^0$. Therefore the machine EMF E is primarily along the rotor q axis. Consider a machine having a constant terminal voltage $V$ .For generator action the phasor $\overline{E}$ should be leading the phasor $\overline{V}$ .The angle between $\overline{E}$ and $\overline{V}$ is the machine torque angle $\delta$ if the phasor $\overline{V}$ is in the direction of reference phase (phase a).

At t=0 the phasor $\overline{V}$ is located at the axis of phase a, i.e., at the reference axis in fig(2.1). The *q* axis is located at an angle $\delta$, and the *d* axis is located at $\theta = \delta + \pi/2$ . At t>0, the reference axis is located at an angle $w_R t$ with respect to the axis of phase *a*. The *d* axis of the rotor is therefore located at

$$\theta = w_R t + \delta + \pi / 2 \quad \text{rad} \tag{2.6}$$

where $w_R$ is the rated (synchronous) angular frequency in rad/s and $\delta$ is the synchronous torque angle in electrical radians.

Expressions similar to (2.3) may also be written for voltages or flux linkages: e.g.,

$$v_{0dq} = P_{v_{abc}} \qquad \lambda_{0dq} = P\lambda_{abc} \tag{2.7}$$

If the transformation (2.5) is unique, an inverse transformation also exist wherein we may write

$$i_{abc} = P^{-1} i_{0dq} \tag{2.8}$$

The inverse of (2.5) may be computed to be

$$P^{-1} = \sqrt{2/3}\begin{bmatrix} 1/\sqrt{2} & \cos\theta & \sin\theta \\ 1/\sqrt{2} & \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) \\ 1/\sqrt{2} & \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) \end{bmatrix} \tag{2.9}$$

and we note that $P^{-1} = P^t$, which means that the transformation P is orthogonal .Having P orthogonal also means that the transformation P is power invariant, and we should expect to use the same power expression in either the a-b-c or the 0-d-q frame or reference. Thus

$$\begin{aligned} p &= v_a i_a + v_b i_b + v_c i_c = v_{abc}^t i_{abc} = (P^{-1} v_{0dq})'(P^{-1} i_{0dq}) \\ &= v_{0dq}^t (P^{-1})^t P^{-1} i_{0dq} = v_{0dq}^t P P^{-1} i_{0dq} \\ &= v_{0dq}^t i_{0dq} = v_0 i_0 + v_d i_d + v_q i_q \end{aligned} \tag{2.10}$$

### 2.1.1 TORQUE AND POWER

The total three-phase power output of a synchronous machine is given by

$$P_{out} = v_a i_a + v_b i_b + v_c i_c = v_{abc}^t i_{abc} \quad \text{pu} \tag{2.11}$$

where the superscript ***t*** indices the transpose of $v_{abc}$. But from (4.8) we may write $i_{abc} = P^{-1} i_{0dq}$ with a similar expression for the voltage vector. Then (2.11) becomes

$$P_{out} = v_{0dq}^t (P^{-1})^t P^{-1} i_{0dq}$$

Performing the indicated operation and recalling that P is orthogonal, we find that the power output of a synchronous generator is invariant under the transformation P; i.e.,

$$P_{out} = v_d i_d + v_q i_q + v_0 i_0 \tag{2.12}$$

For simplicity we will assume balanced but not necessarily steady-state conditions. Thus $v_0 = i_0 = 0$ and

$$P_{out} = v_d i_d + v_q i_q \quad \text{(balanced condition)} \tag{2.13}$$

Substituting for $v_d$ and $v_q$

$$P_{out} = (i_d \lambda_d + i_q \lambda_q) + (i_q \lambda_d - i_d \lambda_q)w - r(i_d^2 + i_q^2) \tag{2.14}$$

It observes that the three terms are identifiable as the rate of rate of change of stator magnetic field energy, the power transferred across the air gap, and the stator ohmic losses respectively. The machine torque is obtained from the second term,

$$T_{e\phi} = \partial W_{fld} / \partial\theta = \partial P_{fld} / \partial w = \partial / \partial w\left[(i_q \lambda_d - i_d \lambda_q)w\right] = i_q \lambda_d - i_d \lambda_q \text{ pu} \tag{2.15}$$

The mathematical model of synchronous machine, taking into account the various effects introduced by different rotor circuits,i.e. both field effects and damper-winding effects.The model includes nonlinear equation. In this model the saturation effect is neglected.

## 2.2 MODEL OF AUTOMATIC VOLTAGE REGULATOR AND POWER SYSTEM STABILIZER:

A Power System Stabilizer (PSS) which is installed in the Automatic Voltage Regulator of the Generator can improve the power system stability[18,35]. Therefore the PSS has excellent cost performance rather than constructions of power system arrangements.

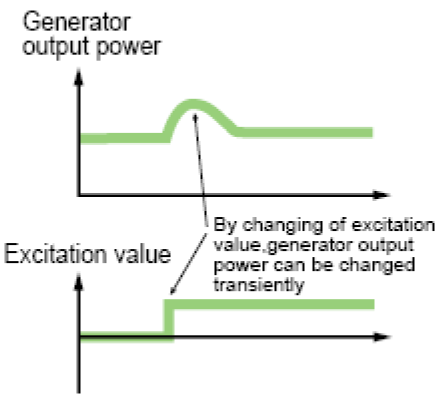


Fig.2.2.variation of excitation value

To change the stability

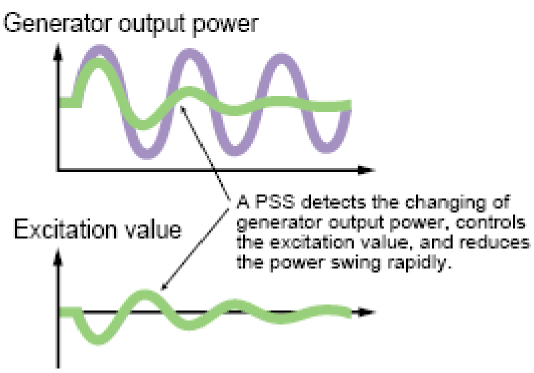


Fig.2.3.Behaviour of PSS

Though a generator output power is decided by the turbine mechanical torque, a generator output power also can be changed by changing excitation value transiently. (Fig.2.2) A PSS detects the changing of generator output power, controls the excitation value, and reduces the power swing rapidly. (Fig.2.3)

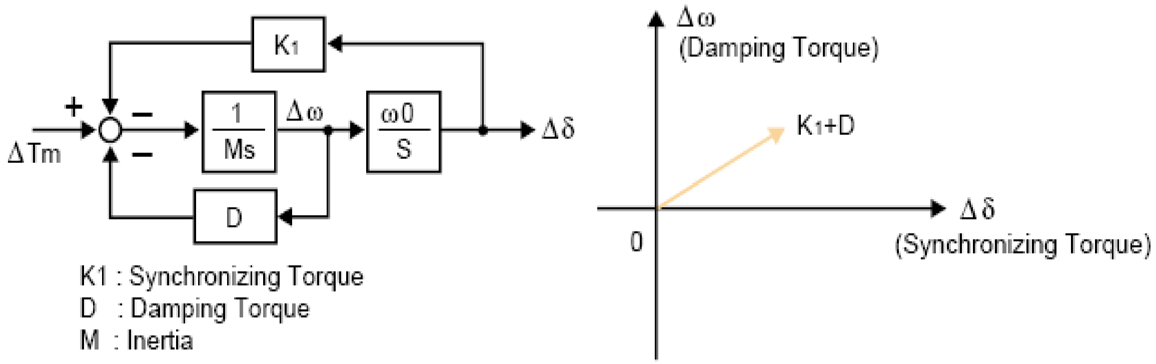


Fig.2.4.Block diagram and phasor diagram of constant excitation system

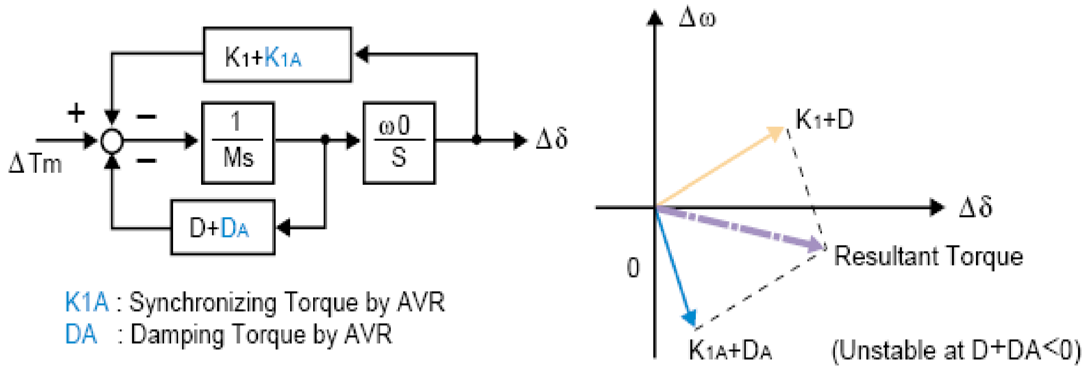


Fig.2.5.Block diagram and phasor diagram of constant excitation system and AVR

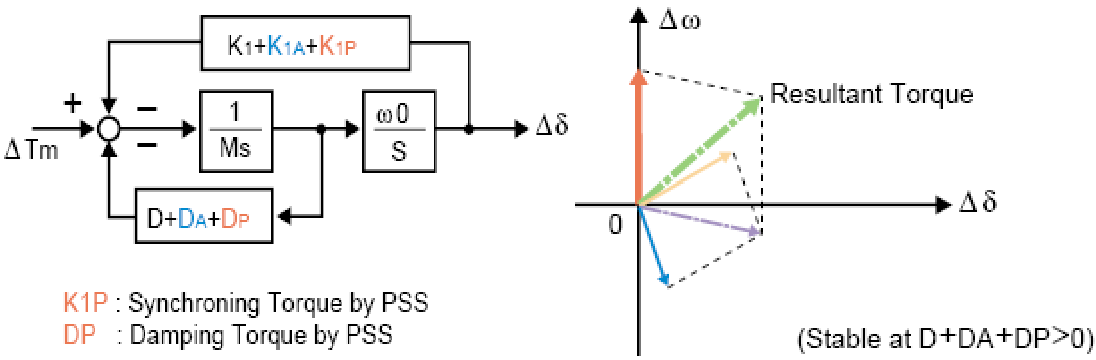


Fig.2.6.Block diagram and phasor diagram of constant excitation system and AVR and PSS

As mentioned before, a PSS detects the changing of generator output power and controls the excitation value. The type of PSS is identified by the detecting signal. The most simple and typical type is Δ P input type. And, recently Δ ω input type and/or Δ f input type PSS also adopted in order to improve a stability of inter-area mode due to the recent increase in power system and power re-routing.

# Chapter 3

# UNIFIED POWER FLOW CONTROL (UPFC)

# UNIFIED POWER FLOW CONTROLLER (UPFC)

## 3.1 A REVIEW ON UPFC

The UPFC is the most versatile FACTS-equipment and is able to insert a voltage in series with the line. This voltage can have any phase and magnitude referred to the line voltage. The UPFC consists of a parallel and a series branch, each consisting of a three-phase transformer and a PWM converter. Both converters are operated from a common dc link with a dc storage capacitor. The real power can freely flow in either direction between the two-ac branches. Each converter can independently generate or absorb reactive power at the ac output terminals [31-34]. The controller provides the gating signals to the converter valves to provide the desired series voltages and simultaneously drawing the necessary shunt currents,

In order to provide the required series injected voltage, the inverter requires a dc source with regenerative capabilities. One possible solution is to use the shunt inverter to support the dc bus voltage. The pulse width modulation (PWM) technique is used to provide a high-quality output voltage, to reduce the size of the required filter, and to achieve a fast dynamic response[19]. The harmonics generated by the inverter are attenuated by a second order filter, providing a low **THD** voltage to the transformer [36].

The Unified Power Flow Controller (UPFC) was proposed' for real turn-off time control and dynamic compensation of ac transmission systems, providing the necessary functional flexibility required to solve many of the problems facing the utility industry. The Unified Power Flow Controller consists of two switching converters, which in the implementations considered are voltage sourced inverters using gate thyristor valves, as illustrated in Fig.3.1. These inverters, labeled "Inverter1" and "Inverter 2" in the figure, are operated from a common dc link provided by a dc storage capacitor. This arrangement functions as an ideal auto ac power converter in which the real power can freely flow in either direction between the ac terminals of the two inverters and each inverter can independently generate (or absorb) reactive power at its own ac output terminal since the series branch of the UPFC can inject a voltage with variable magnitude and phase angle it can exchange real power with the transmission line. However a UPFC as a whole cannot supply or absorb real power in steady state (except for the power drawn to compensate for the losses). Unless it has a power source at its DC terminals. Thus the shunt branch is required to compensate (from the system for any real power drawn/supplied by the series branch and the losses. if the power balance is not maintained, the capacitor cannot remain at a constant voltage.

Shunt branch can independently exchange reactive power with the system.

The main advantage of the power electronics based FACTS controllers is their speed. Therefore the capabilities of the UPFC need to be exploited not only for steady state load flow control but also to improve stability.

A control strategy, in general, should preferably have the following attributes:

- Steady state objectives (i.e. real and reactive power flows) should be readily achievable by setting the references of the controllers.
- Dynamic and transient stability improvement by appropriate modulation of the controller references. While the application of UPFC for load flow control and in stability improvement has been discussed in [33, 34], a detailed discussion on control strategy for UPFC in which we control real power flow through the line, while regulating magnitudes of the voltages at its two ports.

Inverter 2 provides the main function of the UPFC by injecting a voltage $V_{pq}$ with controllable magnitude $V_{pq}$ ($0 \leq Vpq \leq Vpq$) and phase angle $\rho$ ($0 \leq \rho \leq 360$ degree), at the power frequency, insert with line via an insertion transformer. This injected voltage can be considered essentially as a synchronous ac voltage source. The transmission line current flows through this voltage source resulting in real and reactive power exchange between it and the ac system. The real power exchanged at the ac terminal (i.e., at the terminal of the insertion transformer) is converted by the inverter into dc power, which appears at the dc link as positive or negative real power demand. The reactive power exchanged at the ac terminal is generated internally by the inverter.

The basic function of Inverter 1 is to supply or absorb the real power demanded by Inverter 2 at the common dc link. This dc link power is converted back to ac and coupled to the transmission line via a shunt-connected transformer. Inverter 1 can also generate or absorb controllable

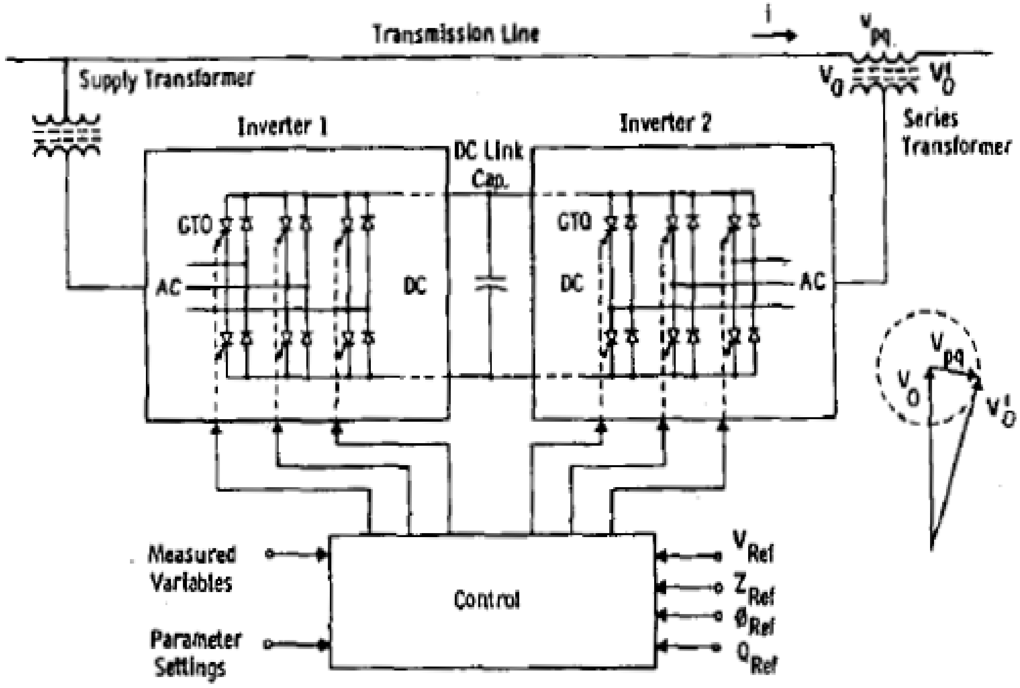

Fig 3.1 Basic circuit arrangement of the Unified Power Flow Controller

reactive power, if it is desired, and thereby it can provide independent shunt reactive compensation for the line. It is important to note that whereas there is a closed "direct" path for the real power negotiated by the action of series voltage injection through Inverters 1 and 2 back to the line, the corresponding reactive power exchanged is supplied or absorbed locally by Inverter 2 and therefore it does not flow through the line. Thus, Inverter 1 can be operated at a unity power factor or be controlled to have a reactive power exchange with the line independently of the reactive power exchanged by Inverter 2. This means that there is no continuous reactive power flow through the UPFC.

Viewing the operation of the Unified Power Flow Controller from the stand point of conventional power transmission based on reactive shunt compensation, series compensation, and phase shifting, the UPFC can fulfill all these functions and thereby meet multiple control objectives by adding the injected voltage Vpq**,** with appropriate amplitude and phase angle, to the terminal voltage $V_o$, Using phasor representation, the basic UPFC power flow control functions are illustrated in Fig.3.2.

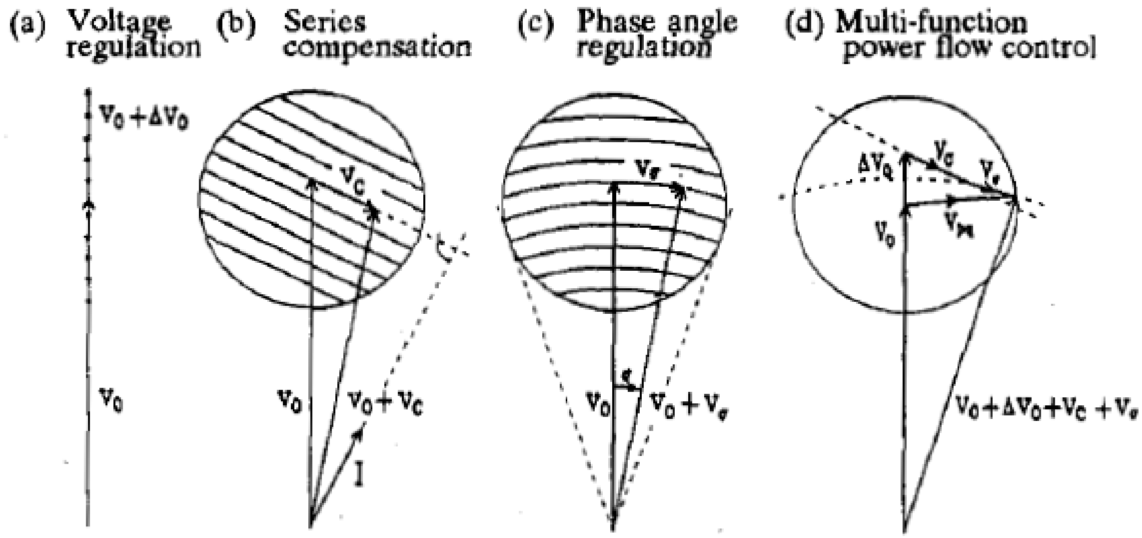


Fig 3.2. Basic UPFC control function. (a)Voltage Regulation (b) Series compensation (c) Angle regulation (d) Multi function power flow controller

Terminal voltage regulation, similar to that obtainable with a transformer tap-changer having infinitely small steps, is shown at (a) where $V_m = \Delta V$(boldface letters represent phasors) is injected in-phase (or anti-phase) with $V_o$ . Series capacitive compensation is shown at (b) where $V_{pq} = V_c$ is injected in quadrature with the line current **I**. Transmission angle regulation (Phase shifting) is shown at (c) where $V_{pq} = V\sigma$ is injected with an angular relationship with respect to $V_o$ that achieves the desired $\sigma$ phase shift (advance or retard) without any change in magnitude. Multi power flow control, executed by simultaneous terminal voltage regulation, series capacitive line compensation, and phase shifting, is shown at (d) where $V_{pq} = \Delta V + V_C + V_\sigma$.

The powerful, hitherto unattainable, capabilities of the UPFC summarized above in terms of conventional transmission control concepts, can be integrated into a generalized power flow controller that is able to maintain prescribed, and independently controllable, real power *P* and reactive power *Q* in the line. Within this concept, the conventional terms of series compensation, phase shifting etc., become irrelevant; the UPFC simply controls the magnitude and angular position of the injected voltage in real time so as to maintain or vary the real and reactive power flow in the line to satisfy load demand and system operating conditions.

## 3.2 BASIC PRINCIPLE OF p and q CONTROL

Consider Fig.3.3. At (a) a simple two machine (or two bus ac inertia) system with sending-end voltage Vs, receiving-end voltage Vr, and line (or tie) impedance X (assumed, for simplicity, inductive) is shown. At (b) the voltages of the system in form of a phasor diagram are shown with transmission angle $\delta$ and $|Vs|=|Vr|$=V. At (c) the transmitted Power P( $P=\left\{\frac{V^2}{X}\right\}\sin\delta$ ) and the reactive power Q =Qs=Qr ( $Q=\left\{\frac{V^2}{X}\right\}\{1-\cos\delta\}$ )supplied at the ends of the line are shown plotted against angle $\delta$. At (d) the reactive power Q=Qr=Qs, is shown plotted against the transmitted power *P* corresponding to the "stable" values of $\delta$ (i.e.,$0\leq\delta\leq90^0$)

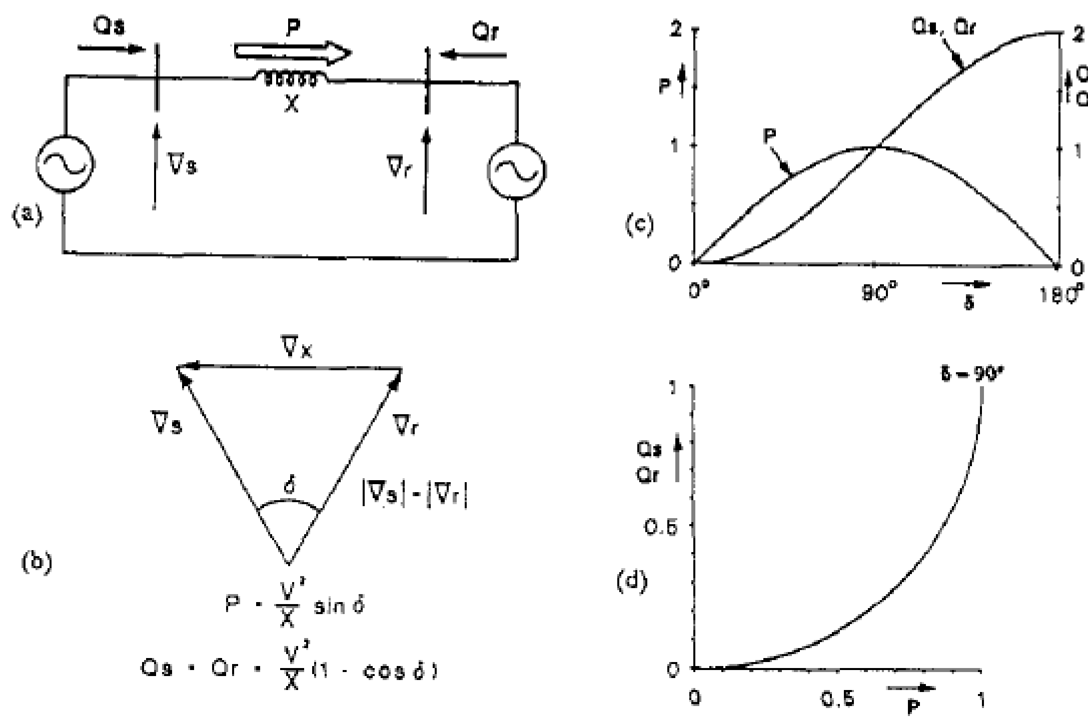


Fig.3.3.Simple two machine system (a) Related voltage phasors (b) Real and Reactive power versus transmission angle (c) sending end and receiving end reactive power versus transmitted real power (d)

The basic power system of Fig.3.3 with the well known transmission characteristics is introduced for the purpose of providing a vehicle to establish the capability of the UPFC to control the transmitted real power *P* and the reactive power demands, *Q,* and *Q,,* at the sending-end and, respectively, the receiving-end of the line.

Consider Fig.3.4 where the simple power system of Fig. 3 is expanded to include the UPFC. The UPFC is represented by a controllable voltage source in series with the line which, as explained in the previous section, can generate or absorb *reactive* power that it negotiates with the line, but the *real* power it exchanges must be supplied to it, or absorbed from it, by the sending-end generator[1,7,17]. The voltage injected by the UPFC in series with the line is represented by phasor V, having magnitude Vpq (0≤Vpq≤0.5 p.u.) and angle $\rho$ ($0 \le \rho \le 360^0$) measured from the given phase position of phasor as illustrated in the figure. The line current, represented by phasor ***I,*** flows through the series voltage source, Vpq and generally results in both reactive and real power exchange. In order to represent the UPFC properly,

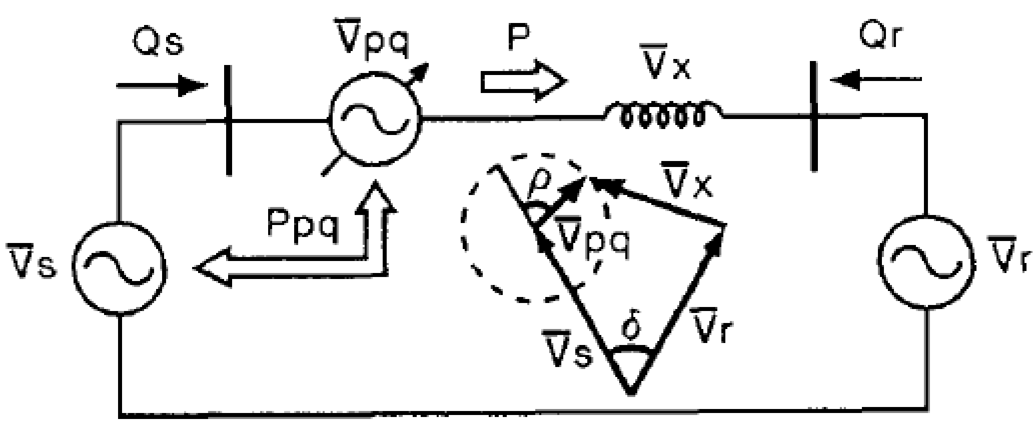


Fig 3.4 Two-machine system with the Unified Power Flow Controller

the series voltage source is stipulated to generate *only* the reactive power *Q,* it exchanges with the line. Thus, the real power *P,* it negotiates with the line is assumed to be transferred to the sending end generator as if a perfect coupling for real power flow between it and the sending-end generator existed. This is in agreement with the UPFC circuit structure in which the dc link between the two constituent inverters establishes a bi-directional coupling for real power flow between the injected series voltage source and the sending end bus. As Fig.3.4 implies, in the present discussion it is further assumed for clarity that the shunt reactive compensation capability of the UPFC is *not* utilized. That is, the UPFC shunt inverter is assumed to be operated at unity power factor, its sole function being to transfer the real power demand of the series inverter to the sending- end generator. With these assumptions, the series voltage source, together with the real power coupling to the sending-end generator as shown in Fig. 3.4, is an accurate representation of the basic UPFC.

It can be readily observed in Fig. 3.4 that the transmission line "sees" $V_s+V_{pq}$ as the effective sending-end voltage. Thus, it is clear that the UPFC affects the voltage (both its magnitude and angle) across the transmission line and therefore it is reasonable to expect that it is able to control, by varying the magnitude and angle of Vpq the transmittable real power *as well as* the reactive power demand of the line at any given transmission angle between the sending-end and receiving- end voltages.

in fig 3.2(d)

$$V_{pq} = \Delta V + V_q + V_\sigma \tag{3.1}$$

$$P - jQ_r = V_r \left( \frac{V_s + V_{pq} - V_r}{jX} \right)^* \tag{3.2}$$

When Vpq=0 then

$$P - jQ_r = V_r \left( \frac{V_s - V_r}{jX} \right)^* \tag{3.3}$$

Thus with Vpq $\neq 0$ then

$$P - jQ_r = V_r \left( \frac{V_s - V_r}{jX} \right)^* + \frac{V_r \overset{*}{V}_{pq}}{-jX} \tag{3.4}$$

Substituting

$$V_s = Ve^{j\delta/2} = V(\cos\frac{\delta}{2} + \sin\frac{\delta}{2}) \tag{3.5}$$

$$V_r = Ve^{-j\delta/2} = V(\cos\frac{\delta}{2} - \sin\frac{\delta}{2}) \tag{3.6}$$

and

$$V_{pq} = V_{pq}e^{j(\delta/2+\rho)} = V_{pq}\{\cos(\frac{\delta}{2}+\rho) + j\sin(\frac{\delta}{2}+\rho)\} \tag{3.7}$$

The following expressions are obtained for P and $Q_r$

$$P(\delta,\rho) = P_0(\delta) + P_{pq}(\rho) = \frac{V^2}{X}\sin\delta - \frac{VV_{pq}}{X}\cos(\frac{\delta}{2}+\rho) \tag{3.8}$$

and

$$Q_r(\delta,\rho) = Q_{0r}(\delta) + Q_{pq}(\rho) = \frac{V^2}{X}(1-\cos\delta) - \frac{VV_{pq}}{X}\sin(\frac{\delta}{2}+\rho) \tag{3.9}$$

where

$$P_0(\delta) = \frac{V^2}{X}\sin\delta$$

and

$$Q_{0r}(\delta) = -\frac{V^2}{X}(1-\cos\delta)$$

since angle $\rho$ is freely varies between 0 and $2\pi$ at any given transmission angle $\delta\,(0 \le \delta \le \pi)$.It follows that $P_{pq}(\rho)$ and $Q_{pq}(\rho)$ are controllable between $-\frac{VV_{pq}}{X}$ and $+\frac{VV_{pq}}{X}$ independent of angle $\delta$ .therefore the transmittable real power varies between

$$P_0(\delta) - \frac{VV_{pq\max}}{X} \le P_0(\delta) \le P_0(\delta) + \frac{VV_{pq\max}}{X}$$

and the reactive power varies between

$Q_{0r}(\delta)-\frac{VV_{pq\max}}{X} \le Q_{0r}(\delta) \le Q_{0r}(\delta)+\frac{VV_{pq\max}}{X}$ The normalized transmitted active power $P_0(\delta)=\frac{V^2}{X}\sin\delta=\sin\delta$

And the normalized transmitted reactive power $Q_{0r}(\delta)=-\frac{V^2}{X}(1-\cos\delta)$ =(1-cos $\delta$ )

The relationship between real power $P_0(\delta)$ and reactive power $Q_{0r}(\delta)$ can readily be expressed with ($V^2$/X)=1 in the following form.

$$Q_{0r}(\delta)= -1-\sqrt{1-\{P_0(\delta)\}^2} \tag{3.10}$$

or

$$\{Q_{or}(\delta)+1\}^2+\{P_0(\delta)\}^2=1 \tag{3.11}$$

the above equation describes a circle with a radius of 1.0 around the center defined by coordinates P=0 and $Q_r$ = -1 in a {$Q_r$ ,P} plane. Each point of this circle gives the corresponding value of $P_0$ and $Q_{0r}$ values of the uncompensated system at a specific transmission angle $\delta$ .

Assume that Vpq $\neq$ 0.that the real and reactive power change from their uncompensated values , $P_0(\delta)$ and $Q_{0r}(\delta)$,as a function of magnitude Vpq and angle $\rho$ of the injected voltage phasor Vpq Since angle $\rho$ is an unrestricted variable ($0\le \rho \le 2\pi$),The boundary of the attainable control region for P($\delta,\rho$) and $Q_r(\delta,\rho)$ is obtained from a complete rotation of phasor Vpq with its maximum magnitude $V_{pqmax}$ .It follows from the above equation that this control region is a circle with a center defined by coordinates $P_0(\delta)$ and $Q_{0r}(\delta)$ and radius of ($V_rV_{pq}$)/X. The boundary can be described by the following equation:

$$\{P(\delta,\rho)-P_0(\delta)\}^2+\{Q_r(\delta,\rho)-Q_{0r}(\delta)\}^2=\left\{\frac{VV_{pq\max}}{X}\right\}^2 \tag{3.12}$$

The circular region controlled by the above equation for V=1.0.Vpqmax=0.5 and X=1.0 p.u. with their center on the circular arc characterizing the uncompensated system at transmission angle $\delta = 0^0, 30^0, 60^0$, and $90^0$. In other words the center of the control regions are defined by the corresponding $P_0(\delta), Q_{0r}(\delta)$ coordinates at angles $\delta = 0^0, 30^0, 60^0$, and $90^0$ in the $\{Q_r, P\}$ plane.

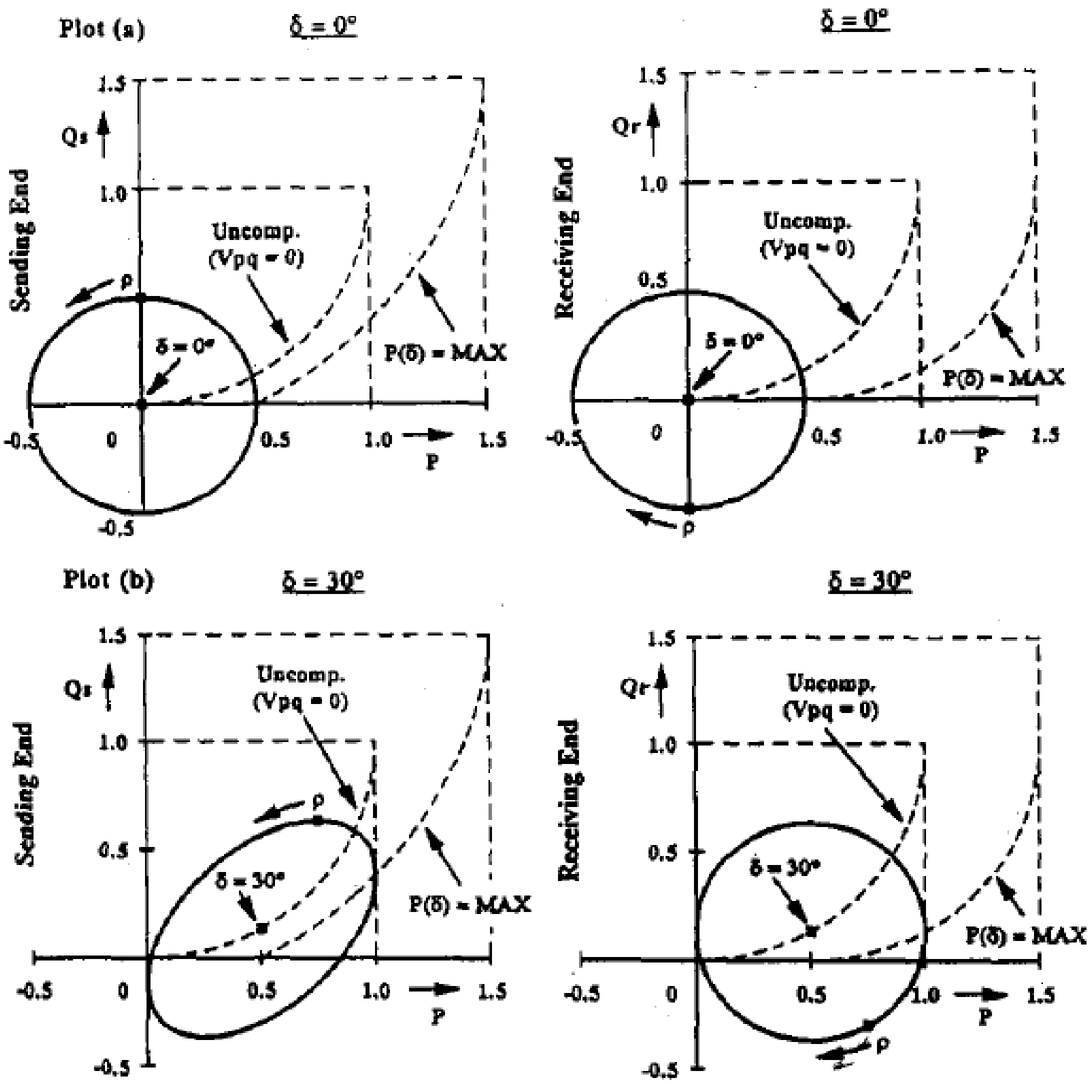


Fig.3.5. Attainable sending –end reactive power vs. transmitted power (left hand side plots) and receiving-end reactive power vs. transmitted power (right hand side plots) values with the UPFC at $\delta = 0^0, \delta = 30^0$

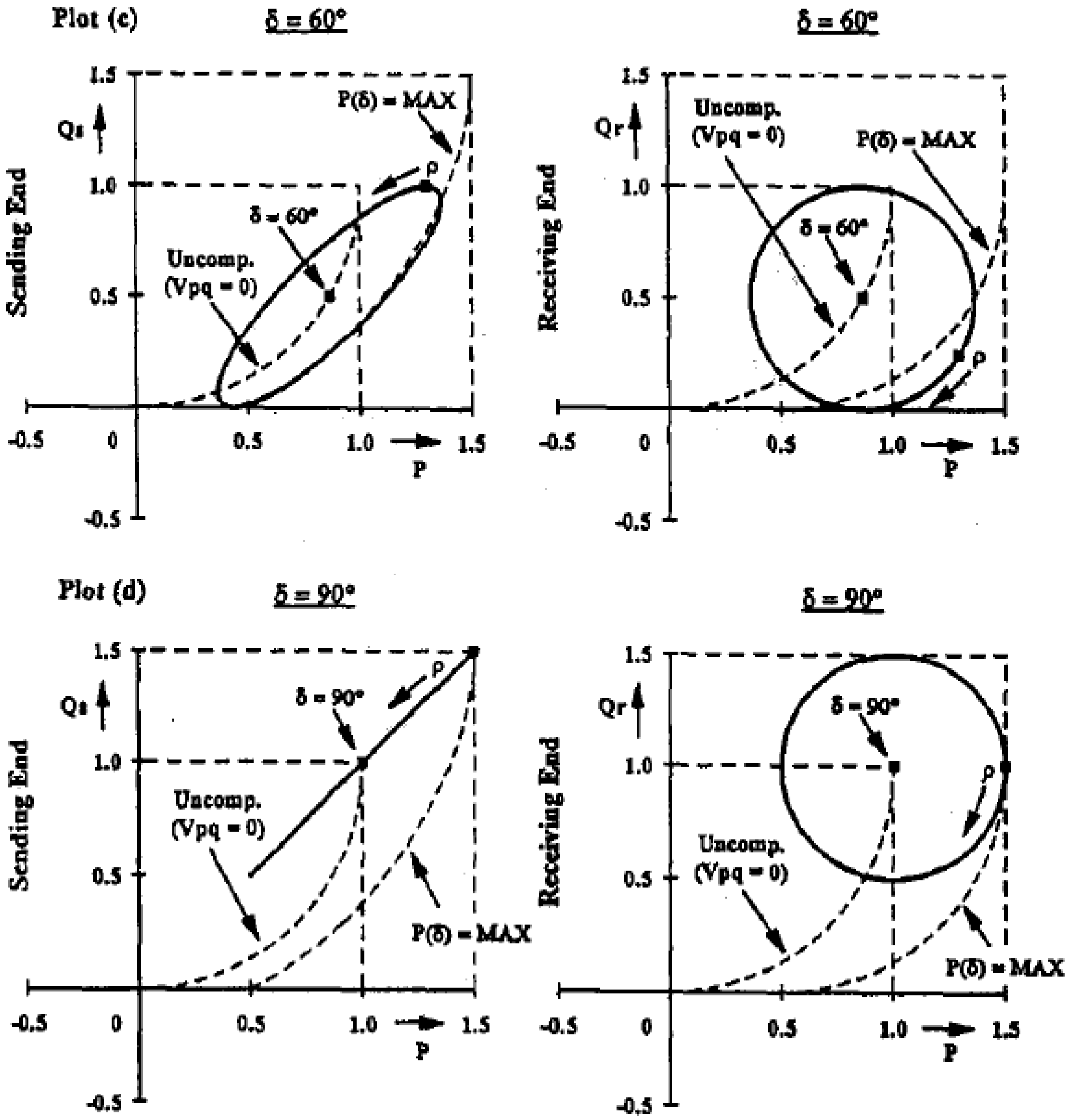


Fig.3.5. Attainable sending –end reactive power vs. transmitted power (left hand side plots) and receiving-end reactive power vs. transmitted power (right hand side plots) values with the UPFC at $\delta = 60^0$ , $\delta = 90^0$

In Fig.3.5 (a) through 3.5(d) the reactive power Qs**,** supplied by the sending- end generator, and Qr is supplied by the receiving-end generator, are shown plotted separately against the transmitted power P **as** a function of the magnitude Vpq and angle $\rho$ of the injected voltage phasor Vpq**,** at four transmission angles: $\delta = 0^0, 30^0, 60^0$, and $90^0$. At Vpq=0**,** each of these plots becomes a discrete point on the basic Q-P curve shown in Fig. 3.5(d), which is included in each of the above figures for reference. The curves showing the relationships between *Qs* and *P,* and *Q,* and *P,* for the transmission angle range of $0 \le \delta \le 90^0$ when the UPFC is operated to provide the maximum transmittable power with no reactive power control (Vpq=Vpqmax and $\rho = \rho_{p=p_{\max}}$)**,** are also shown by a broken-line with the label "P($\delta$)=MAX" at the "sending-end" and, respectively, "receiving-end" plots of the figures.

Consider first Fig. 3.5(a), which illustrates the case when the transmission angle is zero ($\delta$=0) With Vpq=0, *P,* Qs, and *Q*r are all zero, i.e., the system is at standstill at the origins of the *Qs ,P* and *Qr ,P* coordinates. The circles around the origin of the { $Q_s$, *P}* and {Qr,P} planes show the variation of Qs and *P,* and *,Qr* and *P,* respectively, as the voltage phasor Vpq with its maximum magnitude Vpqmax is rotated a full revolution ($0 \le \rho \le 360^0$) . The area within these circles defines all *P* and *Q* values obtainable by controlling the magnitude *V* and angle $\rho$ of phasor Vpq. In other words, the circle in the {Qs,P} and {Qr ,P} planes define all *P* and *Q,* and, respectively, *P* and *Q,* values attainable with the UPFC of a given rating. It can be observed, for example, that the UPFC with the stipulated voltage rating of 0.5 p.u. is able to establish 0.5 p.u. power flow, in either direction, without imposing any reactive power demand on either the sending-end or the receiving-end generator. Of course**,** the UPFC, as seen, *can* force the generator at one end to supply reactive power for the generator at the other end. (In the case of inertia, one system *can* be forced to supply reactive power for the other one.).

In general, at any given transmission angle $\delta$**,** the transmitted real power P, and the reactive power demands at the transmission line ends, Qs and Qr , can be controlled freely by the UPFC within the boundaries obtained in the { *Qs*,P} and {Qr,P} , planes by rotating the injected voltage phasor Vpq with its maximum magnitude a full revolution. The boundary in each plane is centered around the point defined by the transmission angle on the Q versus P curve that characterizes the basic power transmission at Vpq.

Considering next the case of $\delta = 30^0$ (Fig. 3.5b), it is seen that the receiving-end control region in the { Qr, P} plane is again defined by a circle, however, the sending-end control region boundary in the {Qs,P} plane becomes an ellipse. As the transmission angle $\delta$ is further increased, for example, to $60^0$ (Fig. 3.5c), the ellipse defining the control region for P and Qs in the { *Qs*, P} plane becomes narrower and finally at $90^0$ (Fig. 3.5d) it degenerates into a straight line. By contrast, the control region boundary for P and Qr in the {Qr, *P*} plane remains a circle at all transmission angles. Fig.3.5a through 3.5d clearly demonstrate that the UPFC, with its unique capability to control independently the real and reactive power flow at any transmission angle, provides a powerful new tool for transmission system control.

### 3.3 COMPARISON BETWEEN CONVENTIONAL THYRISTOR-CONTROLLED AND UNIFIED POWER-FLOW CONTROLLERS.

Conventional thyristor controlled power controllers employ traditional power system compensation and control schemes, in which thyristor valves replace mechanical switches. Each scheme is devised to control a particular system parameter affecting power flow. Thus, static VAr compensators are applied for reactive power and voltage control, controllable series compensators for line impedance adjustment, and tap-changing transformers for phase-shift. Each of these is a custom-designed system with different manufacturing and installation requirements. Although thyristor controlled power-flow controllers (primarily static VAr compensators) have played a significant role in demonstrating the effectiveness of fast, electronic controls in power system stability improvements, and in this way they have paved the way for the concept of flexible AC transmission systems, they have also revealed the inherent limitations of the conventional approaches with regard to manufacturing and installation complexity, physical size, and relatively high overall cost which is increasingly dominated by that of nonelectronic components and labour.

The unified power-flow controller concept has the potential to overcome the major shortcomings of the conventional thyristor controlled approach [22, 23]. From the technical standpoint, it makes it possible to handle practically all power-flow control and transmission line compensation problems uniformly, using solid-state voltage sources exclusively instead of switched capacitors and reactors, or tap-changing transformers. Apart from the general attractiveness of a universally applicable single compensator/controller device, the voltage source based universal power flow approach provides functional flexibility and operational performance generally not attainable by conventional thyristor-controlled systems. From the equipment and installation standpoints, this approach naturally lends itself to volume production, it minimizes real estate and installation labour requirements, and makes the overall capital cost primarily dependent on the cost of the solid-state components, which historically exhibits the sharpest decreasing trend with technology advances.

### 3.3.1 PERFORMANCE COMPARISON

The unified power flow controller can regulate or vary the line impedance, voltage, and phase angle via a single series voltage-source injection, and generate controllable reactive power for independent shunt compensation. Comparing this to a roughly equivalent arrangement of a thyristor controlled tap changing transformer for phase angle control together with a static VAr compensator for reactive power control, the advantages of the universal power-flow controller become quite obvious. The unified power-flow controller can simultaneously or selectively provide series impedance compensation and phase angle control[16,25]. (The conventional approach would require two totally different, independent equipments to do that.) It internally generates all of the reactive power required to accomplish the power-flow control by series voltage injection. (The conventional phase shifter cannot generate its own reactive power demand; it has to be supplied by the line or, as in the case considered, by a separate controllable VAr source.) It is able to regulate voltage, without additional power hardware, by direct, in-phase voltage injection. (The conventional approach would require another set of 'in-phase' transformer windings with an independent thyristor switch arrangement.) It is capable of providing controllable shunt reactive compensation for the line independently of the reactive power demand of the series voltage injection. (In the conventional combined arrangement of phase shifter and static VAr compensator, the VAr capacity of the compensator is dedicated for the supply of the reactive power demand resulting from the series voltage injection).

The universal power-flow controller is inherently modular. In its most general form (capable of controlling line impedance, voltage, phase angle, and reactive power), it employs two inverters, each with a coupling transformer appropriate for either series or shunt connection. The two inverters are 'back-to-back' connected with a common DC capacitor to accommodate bidirectional real-power transfer between the AC 'input' (shunt) and 'output' (series) terminals. If a specific application requires only controllable shunt or series reactive compensation, the two inverters can be separated, each with its own DC capacitor. In this case, each inverter becomes a self-sufficient VAr source, controlling the voltage of its own DC capacitor by exchanging real power with the AC system. (This is done by introducing a small phase angle between the inverter and AC system terminal voltages.)

The inverter with the parallel coupling transformer (called the advanced static VAr compensator [3.7]) can supply controllable reactive power for shunt compensation (the inverter voltage is in phase with the AC system voltage), and the one with the series injection transformer can provide controllable series compensation (the inverter voltage is in quadrature with the line current). It should be noted for completeness that the shunt compensator arrangement can also be converted into an energy storage system, with independent reactive output power control, by appropriately interfacing its DC terminal with an energy storage device, such as a superconducting coil These two main constituents of the universal power flow controller, when used independently as an advanced static VAr compensator[10,13,15] and controllable series compensator, individually exhibit characteristics superior to those pertaining to their conventional thyristor controlled counterparts.

The advanced static VAr compensator, owing to its superior VI characteristic [12,17,23], can supply full capacitive current at any system voltage down to about 0.15p.u. (thus it needs normally an appreciably lower VAr rating than a conventional SVC whose maximum capacitive output current decreases with voltage - for the same stability improvement or voltage support). In addition, it can have an increased transient rating in both the inductive and capacitive operating regions (the conventional SVC cannot increase the capacitive VAr output above its rated value at, or below, the nominal system voltage).

The advanced controllable series compensator employs no series capacitor and thus it cannot cause sub synchronous resonance; its output is continuously variable with fast response so it can precisely control impedance and damp sub synchronous oscillations caused by existing series capacitors; in addition, it can reverse its output to provide series inductive compensation to decrease excessive line currents. (The conventional thyristor-controlled series compensator, depending on its actual implementation, can provide these features only to a limited degree or not at all.)

### 3.3.2 EQUIPMENT COMPARISON

The unified power-flow controller approach incorporates two basic concepts: one is that all transmission line compensations (shunt or series) can be provided by the same solid-state inverter functioning as a controllable AC voltage source with internal VAr generation capability, and the other one is that two of these basic inverters can be combined into a single unit to provide all power flow compensation (shunt and series) and control functions (direct voltage regulation and phase-shaft) involving both reactive and real power.

From the equipment standpoint, the unified power flow controller is based on a single power electronic hardware building block, the voltage-sourced inverter. This inverter can be constructed from standard six-pulse modules, using GTO valves, in a flexible harmonic neutralized structure for virtually any desired rating. The inverter modules can be produced in volume and pretested. The unified power flow controller approach, apart from the coupling transformers, requires no large AC storage components, such as capacitors and reactors. The real estate requirements are therefore low and the installation labour is minimal.

The hardware implementation of each conventional thyristor-controlled power-flow controller is different. Static VAr compensators use thyristor-switched capacitors and thyristor controlled reactors, operated at a relatively low voltage level on the secondary of a coupling transformer. Controllable series capacitive compensators employ functionally similar components in different circuit configurations, which are operated at transmission line potential and therefore located on a high-voltage platform, with control and cooling provided from ground potential[20,22-18]. The phase shifter requires a completely different thyristor valve structure and a relatively complex transformer with a number of isolated secondary windings. The hardware for each of these applications is essentially custom designed and built. Owing to the presence of AC storage components and their associated (normal or high-voltage) hardware, the conventional reactive compensators are physically large, requiring considerable real estate and installation labour.

Whereas in general the solid-state inverter represents the major capital cost for the unified power-flow controller, the cost of the nonelectronic components and their installation is the major contributor to the overall capital cost of conventional thyristor-controlled installations. Therefore, the cost of the unified power-flow controller is expected to decrease significantly as the GTO thyristor technology matures or advanced power semiconductors are developed. By contrast, semiconductor cost improvements will likely have only a minor impact on the overall cost of conventional thyristor-controlled installations, less than that required to offset the expected cost increases in nonelectronic components and the escalating labour cost.

# Chapter 4

# CONTROL STRATEGY OF UPFC

## 4.1. CONTROL STRATEGY

The main function of UPFC is to control the flow of real and reactive power by injection of a voltage in series with the transmission line. The schematic of UPFC is shown in Fig 4.1 .The UPFC consists of two branches .The series branch of the UPFC can inject a voltage with variable magnitude and phase angle, and the shunt branch is required to compensate( from the system) for any real power drawn , supplied by the series branch and the losses.

$$\Re(\overline{V}^{u1}\overline{I}_1^* + \overline{V}^{u2}\overline{I}_2^*) - P_{loss} = 0 \qquad (4.1)$$

It is this context that suitable control strategies and control design to achieve the same ease of importance.

The control strategies should have the following attributes:

1. Steady state objective should readily achievable by setting the references of the controllers.
2. Dynamic and transient stability improvements.

The UPFC allows us three "degrees of freedom"

1. Magnitude and angle of series voltage
2. Shunt reactive current.

The real and reactive power flow in the line can be con-trolled independently using the series injected voltage [29-31].

It should be noted that the UPFC uses Voltage Source Converters (VSCs) for series voltage injection as well as shunt current control. The injection of series voltage can respond almost instantaneously to an order. The shunt current, however, is controlled indirectly by varying the shunt converter voltage (closed loop control of shunt cur-rent is required).

### 4.1.1 Series injected voltage control

To achieve real and reactive power flow control we need to inject series voltage of the appropriate magnitude and angle. The injected voltage can be split into two components which are in phase ("real voltage") and in quadrature ("reactive voltage") with the line current. It is to be noted that the line current measurement is locally available. The real power can be effectively controlled by varying the series reactance of the line. Reactive voltage injection is like series insertion of reactance except that the injected voltage can be

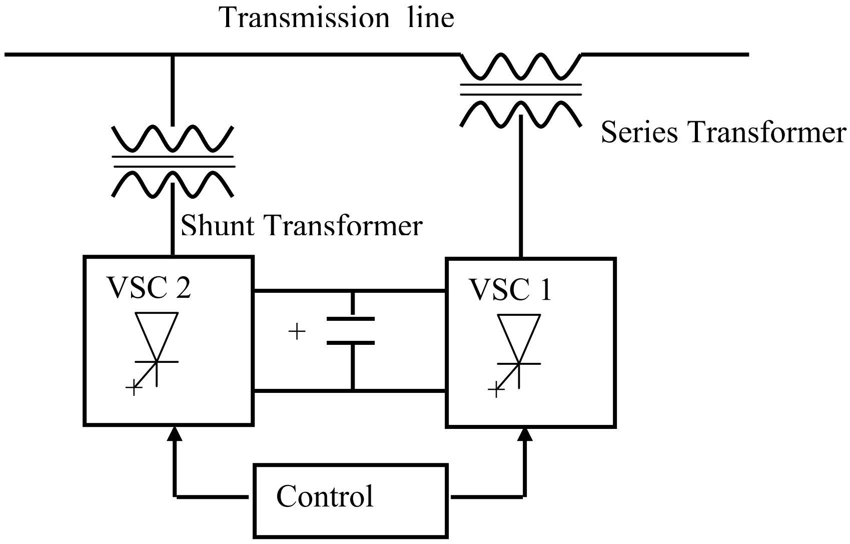


Fig.4.1Unified Power Flow Controller (UPFC)

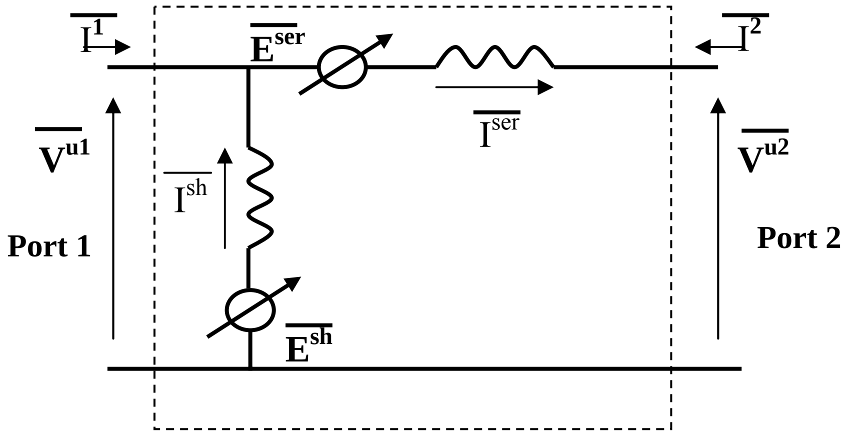


Fig.4.2 UPFC as a two-port device

independent of the transmission line current. Thus we control active power flow using the reactive voltage. It should be kept in mind that real and reactive power references are obtained from (steady state) power flow requirements. The real power reference can also be modulated to improve damping and transient stability.

In addition, reactive power can be controlled to prevent dynamic over/undervoltages. In fact, instead of having closed loop control of reactive power using the voltage, the voltage at port 2 (see Fig.4.2) of the UPFC can be controlled readily by *calculating* the required real voltage to be injected. We can control reactive power in-directly by changing the voltage reference for port 2.

### 4.1.2 Shunt current control

It is well known that shunt reactive power injection can be used to control bus voltage. Thus the shunt current is split into real (in phase with bus voltage) and reactive current components. The reference value for the real current is set so that the capacitor voltage is regulated (which implies power balance). The reactive current reference is set by a bus voltage magnitude regulator (for port 1 of the UPFC).The voltage reference of the voltage regulator itself can be varied (slowly) so as to meet steady state reactive power requirements.

## 4.2 CONTROLLER DESIGN

To simplify the design procedure we carry out the design for the series and shunt branches separately. In each case, the external system is represented by a simple equivalent. The design has to be validated when the various subsystems are integrated. The design tasks are listed below:

1. Series injected voltage control
    a. Power Flow control using reactive voltage.
    b. UPFC port 2 voltage control using real voltage.

2. Shunt converter voltage control
    a. Closed loop current (real and reactive) control.
    b. UPFC port 1 voltage control using reactive current.
    c. Capacitor voltage regulation using real current.

The basic design considerations are illustrated using simplified system models. The performance of all the controllers is subsequently evaluated using detailed simulations for a case study.

### 4.3 SERIES INJECTED VOLTAGE CONTROLLER.

#### 4.3.1 Power Flow Control

In this section we consider the control of real power using reactive voltage (real voltage injection is assumed to be zero). We carry out the analysis on the simplified system shown below in Fig.4.3. The differential equations for the current at port 2 in the D-Q (synchronously rotating at system frequency $\omega_o$) frame of reference [29,30] are given by:

$$\frac{di_D^{ser}}{dt} = -\frac{r_{ser}\omega_b}{x_{ser}} i_D^{ser} - \omega_0 i_Q^{ser} + \frac{\omega_0}{x_{ser}}(v_D^{u2} - v_D^R) \tag{4.2}$$

$$\frac{di_Q^{ser}}{dt} = -\frac{r_{ser}\omega_b}{x_{ser}} i_Q^{ser} - \omega_0 i_D^{ser} + \frac{\omega_0}{x_{ser}}(v_Q^{u2} - v_Q^R) \tag{4.3}$$

where

$$v_D^{u2} = v_D^{u1} + e_D^{esr} \tag{4.4}$$

$$v_Q^{u2} = v_Q^{u1} + e_Q^{esr} \tag{4.5}$$

and, $\omega_b$ is the base frequency. The subscripts 'D' and 'Q' denote the variables in the D-Q frame.

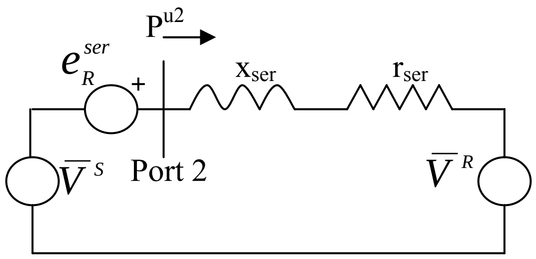


Fig 4.3. Simplified diagram of Unified Power Flow Control

$(v_D^R, v_Q^R)$, $(v_D^{u1}, v_Q^{u1})$ and $(v_D^{u2}, v_Q^{u2})$ are the components of the voltages at the receiving end bus, UPFC port 1 and poK2 respectively. We assume that $\bar{V}^S = \bar{V}^{u1} =$ constant. Power at receiving bus $(e_D^{ser}, e_Q^{ser})$ is approximately equal to that at port 2 $(P^{u2})$ of the UPFC in the steady state; therefore we control the power at port 2 since the feedback signal is readily available.

$$P^{u2} = v_D^{u2} i_D^{ser} + v_Q^{u2} i_Q^{ser} \tag{4.6}$$

Injected reactive and real voltages are written in terms of injected voltages in the D-Q frame $(e_D^{ser}, e_Q^{ser})$ as,

$$e_R^{ser} = e_D^{ser} \cos(\phi^i) - e_Q^{ser} \sin(\phi^i) \tag{4.7}$$

$$e_P^{ser} = e_D^{ser} \sin(\phi^i) + e_Q^{ser} \cos(\phi^i) \tag{4.8}$$

where $\phi^i = \tan^{-1} \dfrac{i_D^{ser}}{i_Q^{ser}}$

For the design of the control of power flow by reactive voltage using output feedback, we examine the transfer function $\left(\dfrac{\Delta P^{u2}(s)}{\Delta u(s)}\right)$ of the linearized system at various operating points. $u(s)$ is the reactive voltage order obtained from the output feedback controller. Since the injection of voltage can respond almost instantaneously to an order, we can assume $e_R^{sh} = e_{Rord}^{sh}$ .

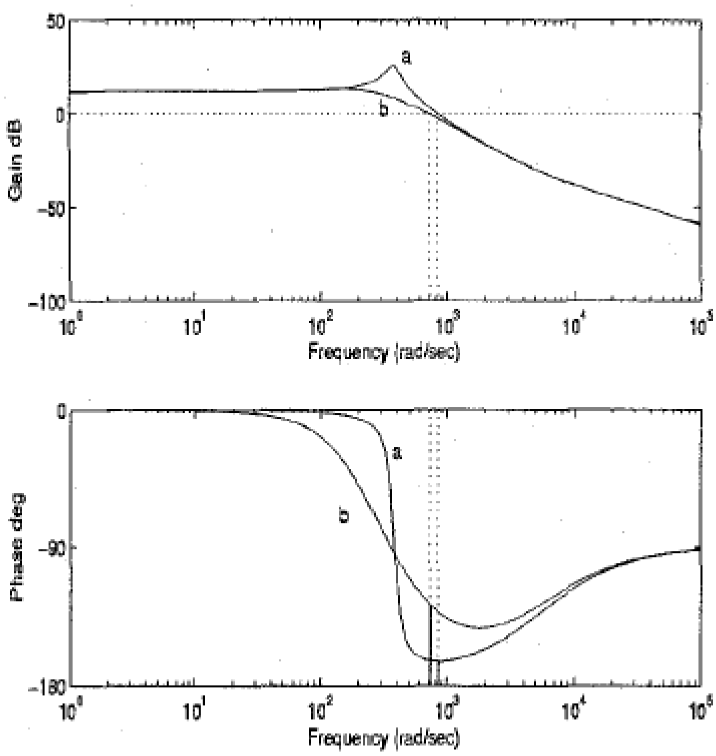


Fig 4.4 Bode Plots of $\dfrac{\Delta P^{u2}}{\Delta u(s)}$

(a) without auxiliary feed-back
(b) with auxiliary feed-back

In Fig. 4.4, we show the Bode plot of the transfer function for quiescent voltage injection =0. The main concern in the design of an output feedback controller is the stability of the oscillatory mode (in the D-Q frame of reference: near about $w_0$ $rad/s$) associated with the series inductance. To make the system more amenable to feedback control we use an auxiliary feedback using the signal,

$$-k\phi^i(s)\frac{sT_\omega}{1+sT_\omega}$$

as shown in Fig.4. 5. Note that the contribution of this auxiliary feedback is zero in steady state. An advantage of using the auxiliary feedback instead of conventional cascade compensators is that even if the output feedback control of active power is not used, the auxiliary signal can
still be used to improve stability of network mode.

From the bode plot, it is seen that the transfer function ($\frac{\Delta P^{u2}}{\Delta u(s)}$) with the auxiliary feedback has a vastly improved phase margin. This allows larger gain to be used in the output feedback controller with a consequence speeding up the response.

While the plots are shown for one operating point $e_{R0}^{ser} = 0$ ,the improvement is there for positive and negative $e_{R0}^{ser}$ also.

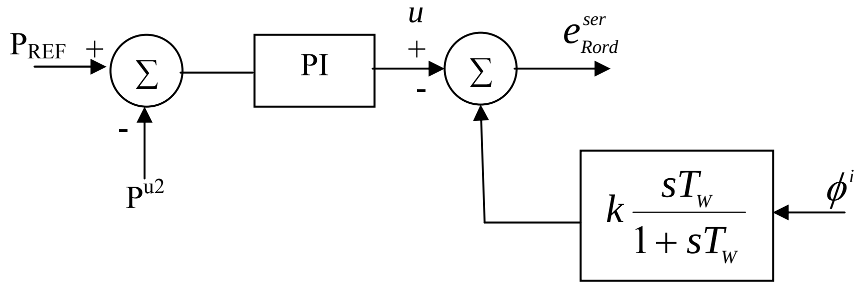


Fig.4.5. Real Power Controller

### 4.3.2 Port 2 voltage controls

The voltage at port 2 of the UPFC is algebraically related to that at port 1 and the reactive voltage injected ($e_R^{ser}$) for power flow control. (For simplicity the series transformer reactance is clubbed with the line impedance). The voltage relation is given by

$$\begin{aligned} V^{u2} &= \sqrt{(V_D^{u2})^2 + (V_Q^{u2})^2} \\ &= \sqrt{(v_D^{u1} + e_D^{esr})^2 + (v_Q^{u1} + e_Q^{esr})^2} \\ &= \sqrt{(v_R^{u1} + e_R^{esr})^2 + (v_P^{u1} + e_P^{esr})^2} \end{aligned} \tag{4.9}$$

$$v_R^{u1} = v_D^{u1}\cos(\phi^i) - v_Q^{u1}\sin(\phi^i) \tag{4.10}$$

$$v_P^{u1} = v_D^{u1}\sin(\phi^i) + v_Q^{u1}\cos(\phi^i) \tag{4.11}$$

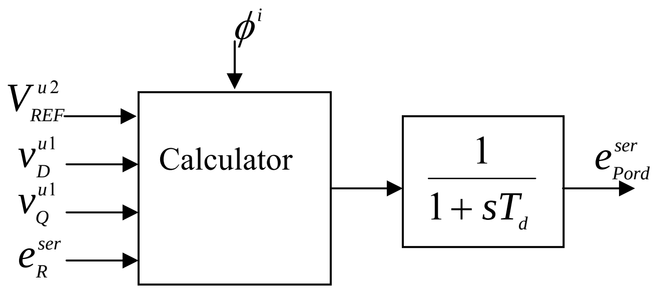


Fig.4.6. Port 2 Voltage Controller

Since all quantities are locally available, we can easily calculate real voltage $e_P^{ser}$ to be injected to obtain desired magnitude of $V^{u2}$ (see Fig.4.6). Note that there are two solutions of $e_P^{ser}$ the solution which has a lower magnitude is chosen.

### 4.4 SHUNT CURRENT CONTROL

The shunt current is controlled by varying the magnitude and angle of the shunt converter voltage (see Fig.4. 2). The dynamical equations in the D-Q frame are given by,

$$\frac{di_D^{sh}}{dt} = -\frac{r_{sh}\omega_b}{x_{sh}} i_D^{sh} - \omega_0 i_Q^{sh} + \frac{\omega_b}{x_{sh}}(e_D^{sh} - v_D^{u1}) \tag{4.12}$$

$$\frac{di_Q^{sh}}{dt} = -\frac{r_{sh}\omega_b}{x_{sh}} i_Q^{sh} + \omega_0 i_Q^{sh} + \frac{\omega_b}{x_{sh}}(e_Q^{sh} - v_Q^{u1}) \tag{4.13}$$

where,

$r_{sh,}$ $x_{sh}$ =shunt transformer resistance and leakage reactance respectively.

$e_D^{sh}, e_Q^{sh}$ =converter output voltage components.

$v_D^{u1}, v_Q^{u1}$ l=voltage components at the bus into which current is injected (port 1 of the UPFC).

Reactive and Real current are defined as

$$i_R^{sh} = i_D^{sh}\cos(\theta^{u1}) - i_Q^{sh}\sin(\theta^{u1}) \tag{4.14}$$

$$i_Q^{sh} = i_D^{sh}\sin(\theta^{u1}) + i_Q^{sh} cos(\theta^{u1}) \tag{4.15}$$

where

$$\theta^i = \tan^{-1}\frac{v_D^{u1}}{v_Q^{u1}}$$

$$V^{u1} = \sqrt{(V_D^{u1})^2 + (V_Q^{u1})^2}$$

For control of shunt current we proceed in a way similar to the one outlined by Schauder and Mehta[4.6]. We can rewrite the differential equations as

$$\frac{di_R^{sh}}{dt} = -\frac{r_{sh}\omega_b}{x_{sh}} i_R^{sh} - \omega i_P^{sh} + \frac{\omega_b}{x_{sh}} e_R^{sh} \tag{4.16}$$

$$\frac{di_P^{sh}}{dt} = -\frac{r_{sh}\omega_b}{x_{sh}} i_P^{sh} + \omega i_R^{sh} + \frac{\omega_b}{x_{sh}}(e_R^{sh} - V^{u1}) \tag{4.17}$$

Note that

$$e_R^{sh} = e_D^{sh}\cos(\theta^{u1}) - e_Q^{sh}\sin(\theta^{u1}) \tag{4.18}$$

$$e_P^{sh} = e_D^{sh}\sin(\theta^{u1}) + e_Q^{sh} cos(\theta^{u1}) \tag{4.19}$$

$$\omega = \omega_0 + \frac{d\theta^{u1}}{dt} \tag{4.20}$$

If we vary the inverter output voltages as follows,

$$e_R^{sh} = e_{Rord}^{sh} = \frac{w}{w_b} x_{sh} i_P^{sh} + \frac{x_{sh}}{w_b} u_R \tag{4.21}$$

$$e_R^{sh} = e_{Rord}^{sh} = -\frac{w}{w_b} x_{sh} i_R^{sh} + V^{u1} + \frac{x_{sh}}{w_b} u_P \tag{4.22}$$

the differential equations (4.16) and (4.17) get decoupled as follows,

$$\frac{di_R^{sh}}{dt} = -\frac{r_{sh}\omega_b}{x_{sh}} i_R^{sh} + u_R \tag{4.23}$$

$$\frac{di_P^{sh}}{dt} = -\frac{r_{sh}\omega_b}{x_{sh}} i_P^{sh} + u_P \tag{4.24}$$

Independent output feedback control of the currents is achieved by varying $U_R, U_P$ as,

$$u_R(s) = G_{sh}(s)(i_{R_{REF}}^{sh}(s) - i_R^{sh}(s)) \tag{4.25}$$

$$u_P(s) = G_{sh}(s)(i_{P_{REF}}^{sh}(s) - i_P^{sh}(s)) \tag{4.26}$$

$G_{sh}(s)$ is the transfer function of the controller (we have used a PI controller).

The reactive current reference is set by a voltage regulator (PI type) for the UPFC bus (port 1).

The dynamical equation for the capacitor voltage is given by

$$u_R(s) = G_{sh}(s)(i^{sh}_{R_{REF}}(s) - i^{sh}_R(s)) \tag{4.27}$$

$g_{cap}$, $b_{cap}$ are the conductance and susceptance of the capacitor respectively.

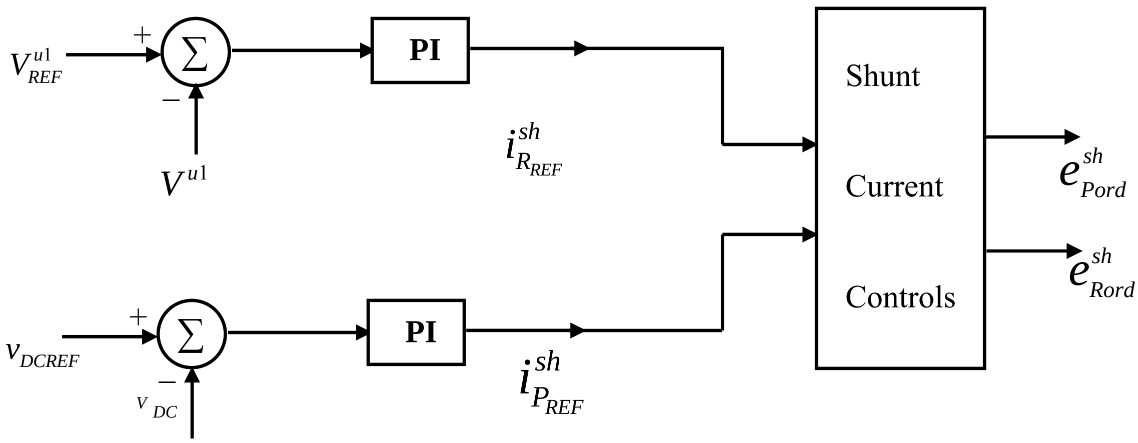


Fig.4.7 Shunt current controller

Any real power drawn/supplied by the series branch (due to $e^{ser}_P$) or by the shunt branch (due to real current injection $i^{sh}_P$) manifests as DC side currents $i^{ser}_{DC}$ and $i^{sh}_{DC}$ respectively. Since we allow variable real series voltage injection, and due to the losses, the capacitor voltage tends to change. To compensate this by $i^{sh}_{DC}$, we set the real current reference ($i^{sh}_{P_{REF}}$) as the output of a PI type capacitor voltage regulator. The controller block diagram is shown in Fig.4.7. The output of the shunt controller gives the desired value of real and reactive voltage which will controls the voltage of the bus .

# Chapter 5

# CASE STUDY OF A THREE-MACHINE NINE-BUS SYSTEM

# CASE STUDY OF A THREE-MACHINE NINE-BUS SYSTEM

## 5.1 CLASSICAL MODEL OF A MULTIMACHINE SYSTEM

The same assumptions used for a system of one machine connected to an infinite bus often assume valid for a multimachine system:

1. Mechanical power input is constant.
2. Damping or asynchronous power is negligible.
3. Constant-voltage-behind-transient-reactance model for the synchronous machines is valid.
4. The mechanical rotor angle of a machine coincides with the angle of the voltage behind the transient reactance.
5. Passive impedances represent loads.

This model is useful foe stability analysis but is limited to the study of transients for only the “first swing” or for periods on the order of one second.

Assumptions 2 are improved upon somewhat by assuming a linear damping characteristic. A damping torque (or power) $D_w$ is frequently added to the inertia torque (or power) in the swing equation. The damping coefficient $D$ includes the various damping torque coefficients, both mechanical and electrical. Values of the damping coefficient usually used in stability studies are in the range of 1-3 pu. [2-5]. This represents turbine damping, generator electrical damping, and the damping effect of electrical loads. However, much larger damping coefficients, up to 25 pu, are reported in the literature due to generator damping alone [2,5,7].

Assumption 5, suggesting load representation by constant impedance, is made for convenience in many classical studies. Loads have their own dynamic behavior, which is usually not precisely known and varies from constant impedance to constant MVA. This is a subject of considerable speculation, the major point of agreement being that constant impedance is an inadequate representation. Load representation can have a marked effect on stability results

## 5.2 CLASSICAL STABILITY STUDY OF A NINE-BUS SYSTEM

The classical model of a synchronous machine may be used to study the stability of a power system for a period of time during which the system dynamic response is dependent largely on the stored kinetic energy in the rotating masses. For many power systems this time is on the order of one second or less. The classical model is the simplest model used in studies of power system dynamics and requires a minimum amount of data; hence, such studies can be conducted in a relatively short time and at minimum cost. Furthermore, these studies can provide useful information. For example, they may be used as preliminary studies to identify problem areas that require further study with more detailed modeling. Thus a larger number of cases for which the system exhibits a definitely stable dynamic response to the disturbances under study are eliminated from further consideration.

A classical study will be presented here on a small nine-bus power system that has three generators and three loads[1]. A one-line impedance diagram for the system is given in fig (5.1.). Generator data for three machines are given in Table 5.1. This system, while small, is large enough to be nontrivial and thus permits the illustration of a number of stability concepts and results.

### 5.2.1 Data preparation

In the performance of a transient stability study, the following data are needed:

1. A load-flow study of the pretransient network to determine the mechanical power $P_m$ of the generators and to calculate the values of $E_i \angle \delta_{i0}$ for all the generators.
2. System data as follows:
    a. The inertia constant *H* and direct axis transient reactance $x_d^{'}$ for all generators.
    b. Transmission network impedances for the initial network conditions and the subsequent switchings such as fault clearing and breaker reclosings.

3. The type and location of disturbance, time of switchings, and the maximum time for which a solution is to be obtained.

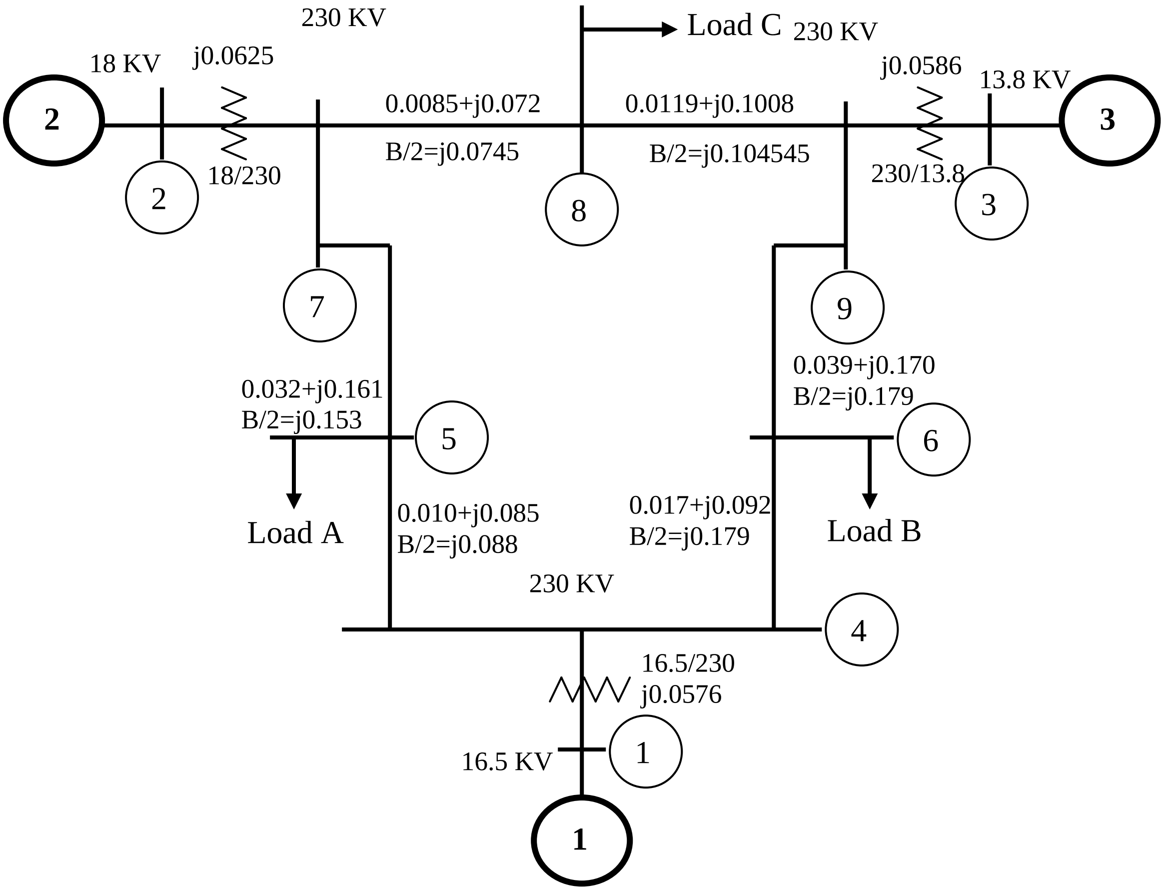


Fig 5.1 Nine-bus system impedance diagram; all impedance are in pu on a 100-MVA

Table 5.1: Generator Data

| Generator | 1 | 2 | 3 |
|---|---|---|---|
| Rated MVA | 247.5 | 192.0 | 128.0 |
| KV | 16.5 | 18.0 | 13.8 |
| Power factor | 1.0 | 0.85 | 0.85 |
| Type | Hydro | Steam | Steam |
| Speed | 180r/min | 3600r/min | 3600r/min |
| $x_d$ | 0.1460 | 0.8958 | 1.3125 |
| $x_d'$ | 0.0608 | 0.1189 | 0.1813 |
| $x_q$ | 0.0969 | 0.8645 | 1.2578 |
| $x_q'$ | 0.0969 | 0.1969 | 0.25 |
| $x_l$(leakage) | 0.0336 | 0.0521 | 0.0742 |
| $r'_{d0}$ | 8.96 | 6.00 | 5.89 |
| $r'_{q0}$ | 0 | 0.535 | 0.600 |
| Stored energy at rated speed | 2364MW-s | 640 MW-s | 301MW-s |

### 5.2.2 Preliminary calculations

To prepare the system data for a stability study, the following preliminary calculations are made:

1. all system data are converted to a common base: a system base of 100MVA is frequently used.
2. the loads are converted to equivalent impedances or admittances. The needed data for this step are obtained from load-flow study. Thus if a certain load bus has a voltage $\bar{V}_L$, power $P_L$, reactive power $Q_L$, and current $\bar{I}_L$ flowing into a load admittance $\bar{Y}_L = G_L + jB_L$, then

   $$P_L + jQ_L = \bar{V}_L \bar{I}_L^* = \bar{V}_L \left[\bar{V}_L^* (G_L - jB_L)\right] = V_L^2 (G_L - jB_L)$$

   The equivalent shunt admittance at that bus is given by

   $$\bar{Y}_L = P_L / V_L^2 - j(Q_L / V_L^2) \tag{5.1}$$

3. the internal voltages of the generators $E_i \angle \delta_{i0}$ are calculated from the load flow data. These internal angles may be computed from the pretransient terminal voltage $V \angle \alpha$ be used as a reference. If we define $\bar{I} = I_1 + jI_2$, then from the relation $P + jQ = \overline{VI}^*$ we have $I_1 + jI_2 = (P - jQ)/V$. But since $E\angle\delta' = \bar{V} + jx_d' \bar{I}$, we compute

   $$E\angle\delta' = (V + Qx_d' / V) + j(Px_d' / V) \tag{5.2}$$

   The initial generator angle is then obtained by adding the pretransient voltage. The prefault network admittances including the load are equivalents are given in the table(5.2) The $\bar{Y}$ matrix of the faulted network and for the faulted network with the fault cleared are similarly obtained.

4. Elimination of the network nodes other than the generator internal nodes by network reduction. The faulted network, and the network with the fault cleared respectively.

Table 5.2 Prefault Network

| | Bus no. | Impedance | | Admittance | |
|---|---|---|---|---|---|
| | | R | x | G | B |
| Generators* | | | | | |
| No.1 | 1-4 | 0 | 0.1184 | 0 | -8.4459 |
| No.2 | 2-7 | 0 | 0.1823 | 0 | -5.4855 |
| No.3 | 3-9 | 0 | 0.2399 | 0 | -4.1684 |
| Transmission Lines | | | | | |
| | 4-5 | 0.0100 | 0.0850 | 1.3652 | -11.6041 |
| | 4-6 | 0.0170 | 0.0920 | 1.9422 | -10.5107 |
| | 5-7 | 0.0320 | 0.1610 | 1.1876 | -5.9751 |
| | 6-9 | 0.0390 | 0.1700 | 1.2820 | -5.5882 |
| | 7-8 | 0.0085 | 0.0720 | 1.6171 | -13.6980 |
| | 8-9 | 0.0119 | 0.1008 | 1.1551 | -9.7843 |
| Shunt admittances | 5-0 | | | 1.2610 | -0.2634 |
| | 6-0 | | | 0.8777 | -0.0346 |
| | 8-0 | | | 0.9690 | -0.1601 |
| | 4-0 | …………………. | | | 0.1670 |
| | 7-0 | | | | 0.2275 |
| | 9-0 | | | | 0.2835 |

# Chapter 6

# RESULTS AND DISCUSSION

## 6.1 A CASE STUDY ON THREE MACHINE NINE BUS SYSTEM

A classical study will be presented here on a The three machine nine bus system shown in Fig.6.1 .The single line impedance for the system is given in that Fig.5.1.The prefault normal load flow solution is given in Fig.6.1.Generator data for the three machines are given in Table 6.1.This system, while small, is large enough to be nontrivial and thus permits the illustration of a number of stability concept and results.

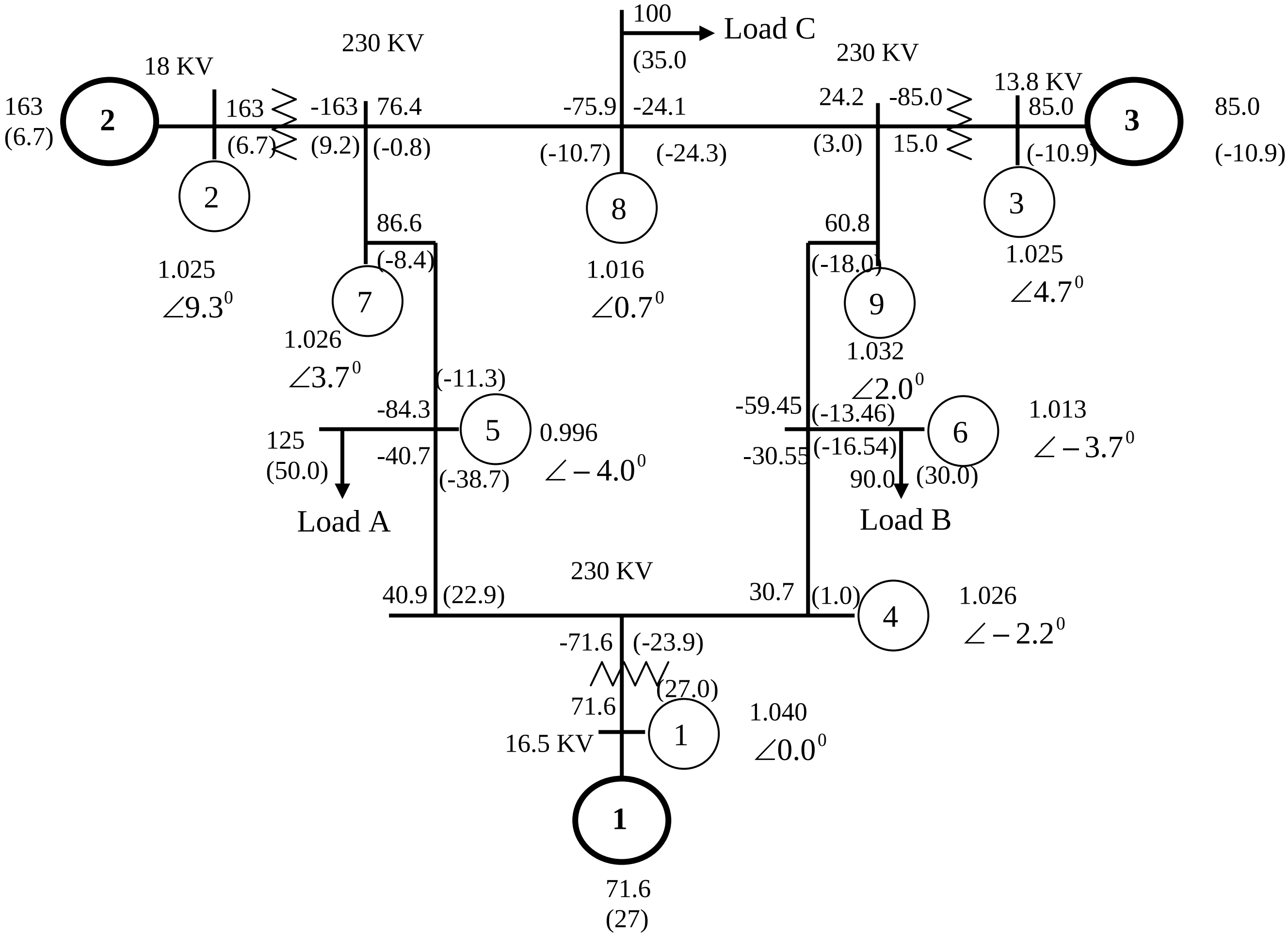


Fig.6.1. Nine –bus system load-flow diagram showing prefault conditions; all flows are in MW and MVAR

In the above system various cases are there;

Case 1: $0 \le t < 1$ Pre Fault condition

Case 2: $1 < t \le 1.25$ During Fault condition (Fault occurred in line 5-7)

Case 3: $1.25 < t \le 2.25$ Post Fault condition (Line 5-7 is removed)

Case 4: $t > 2.25$ Line is restored.

Considering the above cases the behavior of the line is examined here.

The MATLAB simulation result of the power system is shown in the figure given below. The fault occurred during the period between 1 to 1.25 sec. After 1.25 sec the line is removed. The relative variation in rotor angle and the change in angular speed of the rotor is examined. After 1.25 the relative variation in rotor angle and relative change in angular speed starts to damp out. After time 2.25 sec the line is restored. The enhancement of transient stability of the 3 machine nine bus system by the use of UPFC is studied by the comparison simulation results by MATLAB.

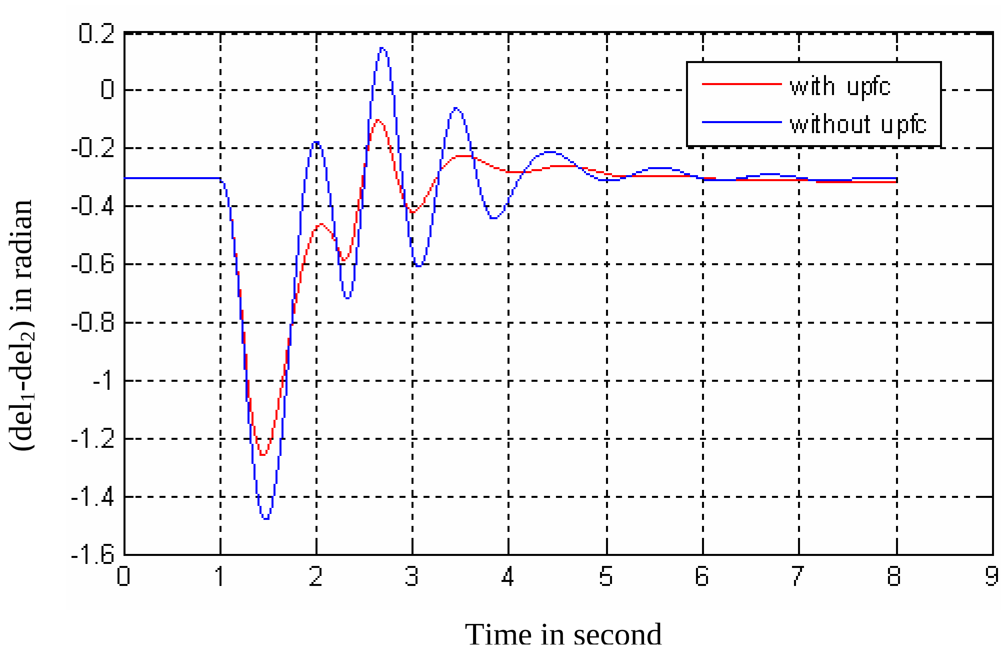


Fig.6.2. Relative change in rotor angle between machine 1 and 2

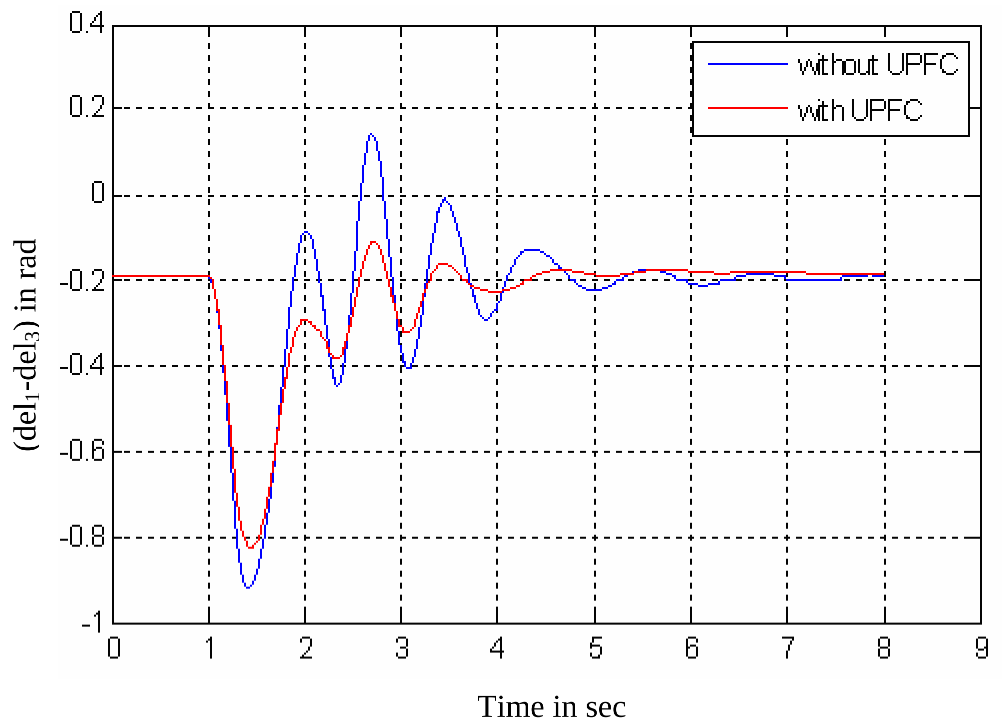


Fig.6.3. Relative change in rotor angle between machine 1 and 3

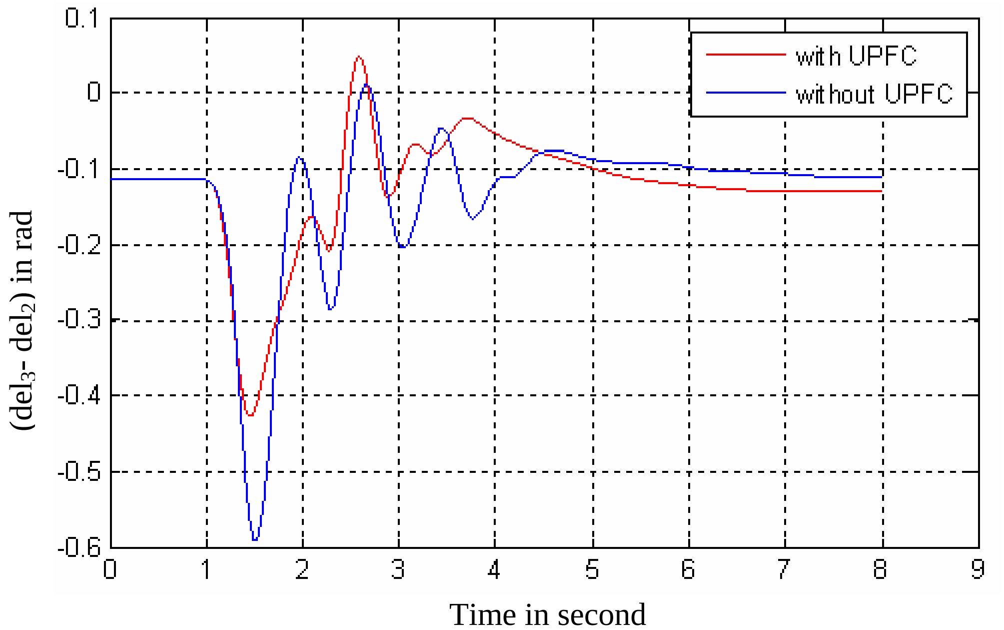


Fig.6.4. Relative change in rotor angle between machine 3 and 2

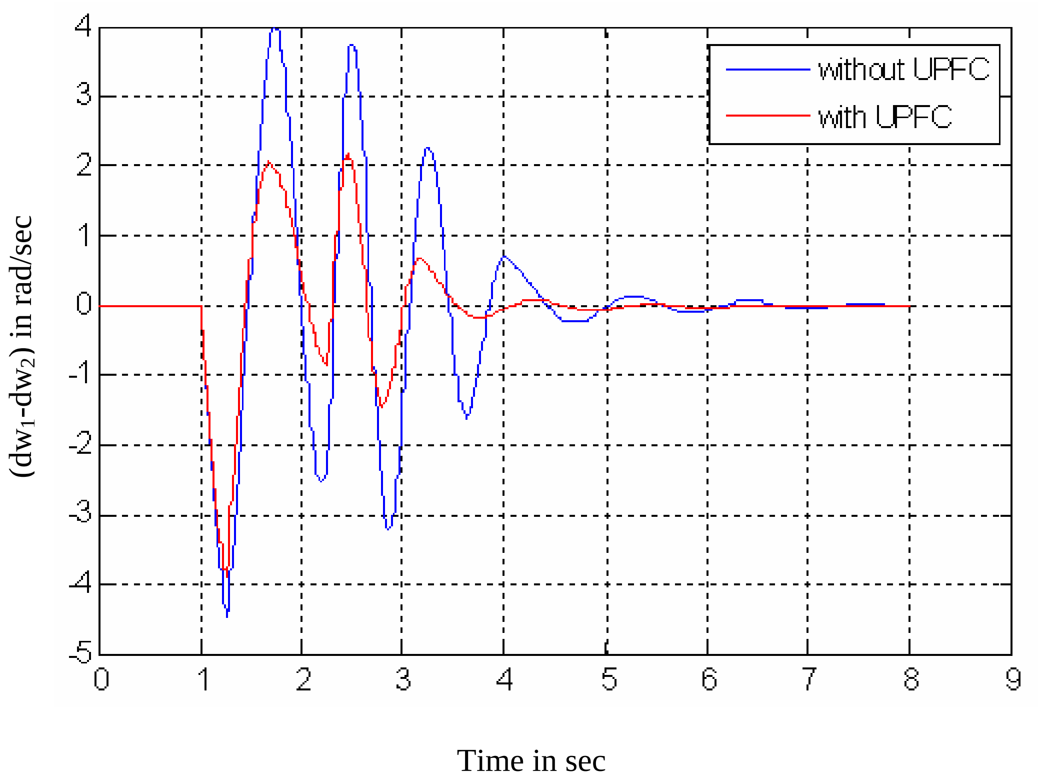


Fig.6.5.Relative change in angular speed between machine 1and 2

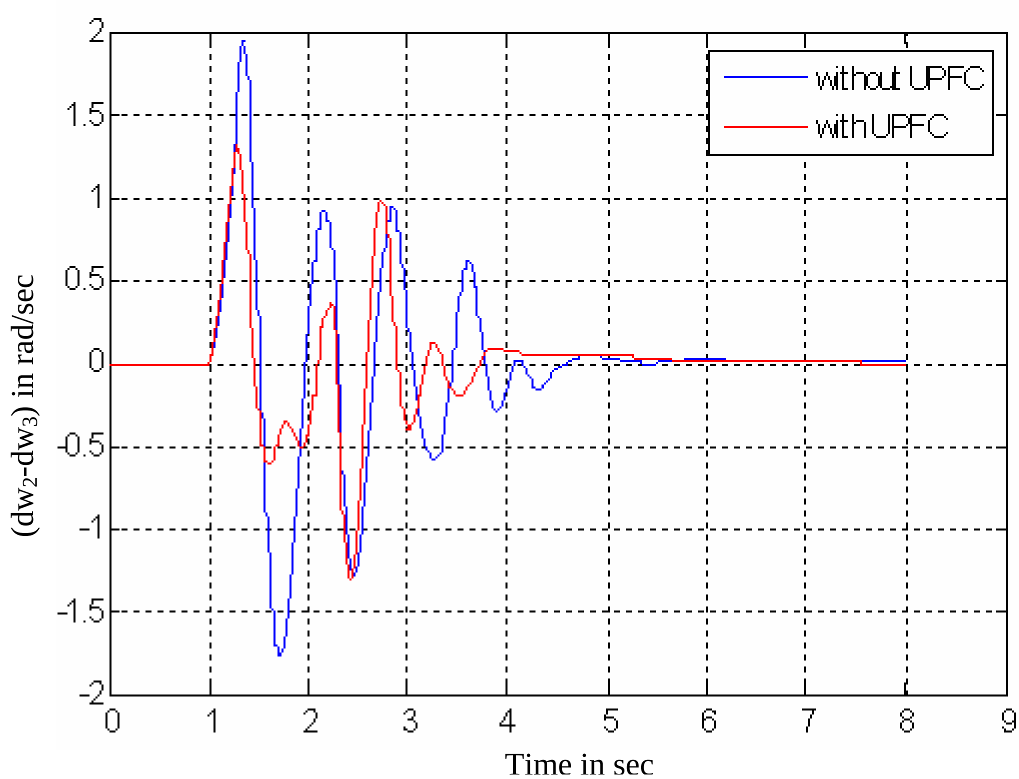


Fig.6.6.Relative change in angular speed between machine 2 and 3

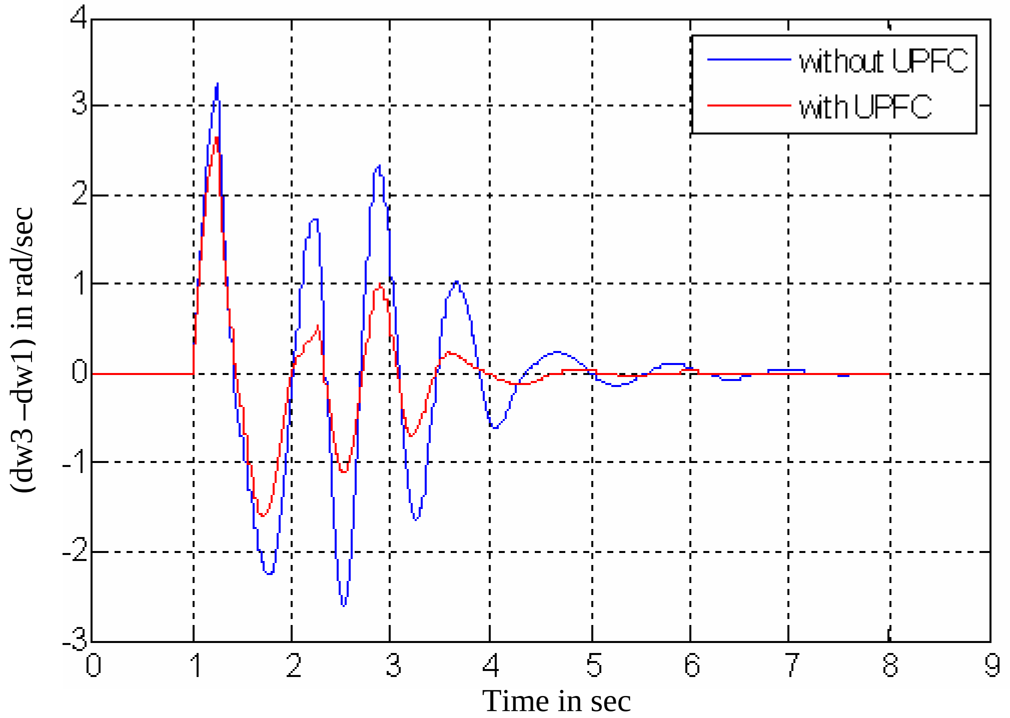


Fig.6.7.Relative change in angular speed between machine 3 and 1

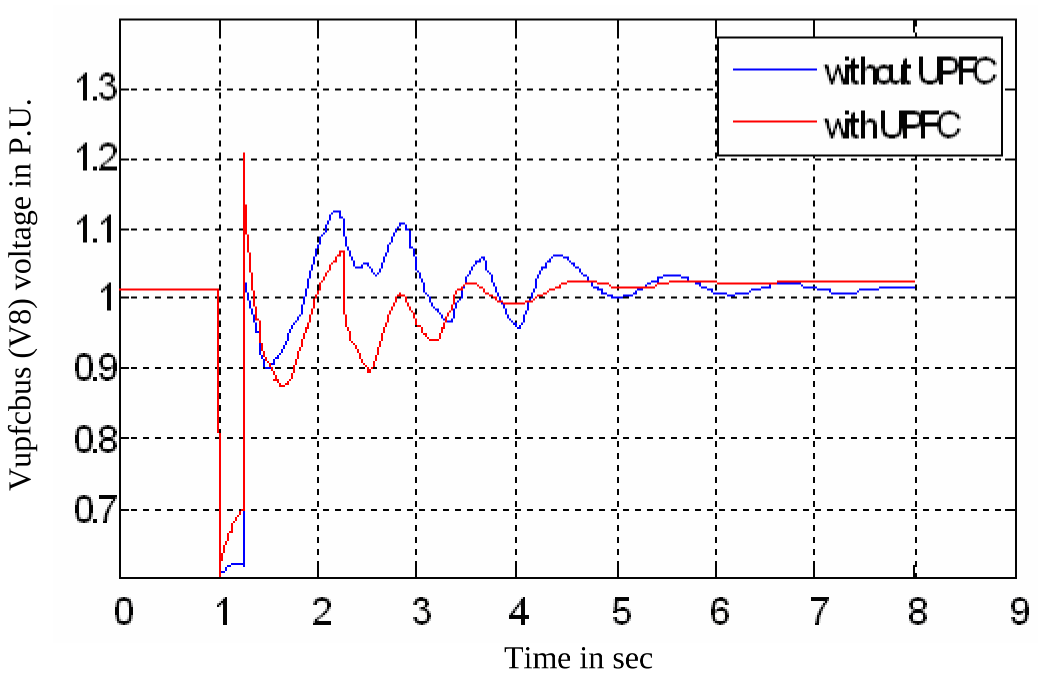


Fig.6.8. The UPFC bus voltage

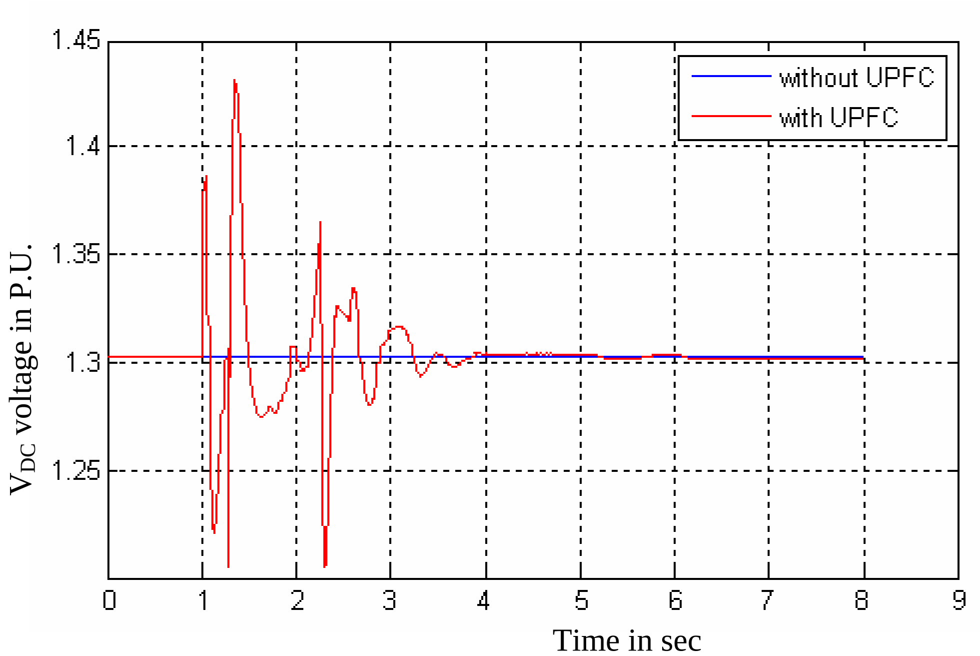


Fig.6.9. The DC link capacitor voltage of the UPFC

# Chapter 7

# CONCLUSIONS AND SUGGESTION FOR FUTURE SCOPE

# CONCLUSIONS AND SUGGESTION FOR FUTURE WORK

## 7.1 CONCLUSIONS

From our proposed technique of adding the UPFC in the transmission line of the power system we get better results as compared to the older techniques power system stabilizer and automatic voltage controller in terms of damping out the transients quickly. We have carried out extensive computer simulations for studying the addition of both series compensation and shunt compensation given by the series controller and the shunt controller. From comparative study of the relative variation in rotor angle and relative change in speed of the three machines nine-bus system with the proposed technique and conventional technique, we have seen that the transient stability is enhanced by the use of UPFC. By using a UPFC we obtain better transient stability performance than the case without a UPFC.

Here we highlight some of the thesis contributions as follows. It describes the role of UPFC on stability improvement of power system. The thesis demonstrates the advantages of using UPFC by presenting a number simulation results.

## 7.2 SUGGESTIONS FOR FUTURE WORK

From our experience on simulation studies we remark that it is difficult to tune the PI controller gain parameters, because it is time consuming and iterative to obtain a good set of values for the gains $K_p$ and $K_I$ . Therefore, in our opinion, an optimization framework can be developed to obtain the values of $K_p$ and $K_I$ , so that the UPFC so designed may yield better performance. Further, there is an opportunity for applying some adaptive control techniques to improve the UPFC performance in place of the fixed gain PI controller.

# Appendix

# APPENDIX

**Exciter Data**

$K_e$=2*[30 200 250]; $T_1$= [0.055 0.188 0.3];

$T_e$= [0.02 0.02 0.02]; $T_2$= [0.033 0.033 0.033];

$T_w$= [1.3 1.4 1.6]; $K_e$= [15 50 10];

$K_{stab}$=.1*[6 9.5 14];

**Shunt Controller Data**:

$r_{sh}$=0.04; $x_{sh}$=0.1; $r_{dc}$=150; $c_{dc}$=5000e-6;

**Series controller data**:

$r_e$=0.0119; $x_e$=0.1008;

**Parameters of AVR and PSS:**

$T_e$=.1; hh=4; $K_e$=50; $k_{pss}$=5; $k_{ipss}$=12;

**The $K_p$ and $K_I$ value:**

$k_{pp}$=100; $k_{ip}$=500;

$k_{pr}$=100; $k_{ir}$=10000;

$k_{pv}$=5; $k_{iv}$=5;

$k_{pvdc}$=.5; $k_{ivdc}$=2;

$k_{ppa}$=0.05; $k_{ipa}$=0;

$k_{pqa}$=0.05; $k_{iqa}$=0;

# References

# REFERENCES


[1]Anderson, P.M., Faud, A.A, Power system control and stability. Galgotia Publication, 1981.

[2]Concordia, C., “Effect of steam turbine reheat on speed-governor performance.”, ASME J. Eng.Power, Volume- 81, (1959):pp.201-206,.

[3]Kirchmayer, L.K., Economic Control of Interconnected Systems, Wiely, NewYork, 1959.

[4]Young, C.C., and Webler R.M., “A new stability program for predicting the dynamic performance of electric power systems”, Proc. Am. Power Conf., Volume-29, (1967): pp.1126-1139.

[5]Byerly, R.T, Sherman D.E., Stability program data preparation manual. Westinghouse Electric Corp., 1970.

[6] Crary S.B., Power System Stability, Volume.2, Wiely, New York, 1947.

[7] Ewart, D.N. ,Flexible AC transmission systems (FACTS) scoping study, 1990

[8] Hingorani, N.G.: ‘High power electronics and flexible AC transmission system’, IEEE Power Eng. Reo., July 1988.

[9] Maliszewski, R.M., Power flow in highly integrated transmission network, CIGRE, 1990

[10]Christl, N. Advanced series compensation with variable impedance, EPRI Workshop on FACTS, Cincinnati, Ohio, USA, November 1990.

[11]Gyugyi, L., “Reactive power generation and control by Thyristor circuits”, IEEE Trans. Ind. Appl., (1979).

[12]Sumi, Y. , “New static VAr control using force-commutated inverters”, IEEE PES Winter Power Meeting, Volume 38 (1981)

[13]Gyugyi, L., “Advanced static VAr compensator using @le turn-off thyristors for utility applications”, CIGRE,1990

[14]Gyugyi, L, “Solid-state control of electric power in AC transmission systems”, International symposium on electric energy converters in power systems, Italy, 1989

[15]Erinmez, LA.,”Static VAr compensators”,Working Group38-01. Task Force No. 2 on SVC, CIGRE, 1986

[16] Wood, P., “Study of improved load tap changing for transformers and phase-angle regulators”, EPRI Report EL-6079, Project 2763-1, 1988.

[17]Hingorani, N.G., “FACTS-flexible AC transmission system”, IEE 5th international conference an AC and DC transmission, London.

[18] Round, S.D., Yu, Q., Norum, L.E., and Undeland, T.M., "Performance of a unified power flow controller using a d-q-control system", IEE conference on AC and DC transmission, London, Volume- 29,( April - May 1996).

[19]Liu, J.Y., Song, Y.H., and Foss, A.M.: " Simulation of the PWM UPFC Using EMTP", "IEE conference on AC and DC power transmission", Volume-29 ,(April - May 1996)

[20]Lombard, X., and Therond, P.G., "Control of unified power flow controller: comparison of methods on the basis of a detailed numerical model", IEEUPES Summer Meeting, (July -August 1996)

[21]Schauder, C., and Mehta, H., "Vector analysis and control of advanced static Var commnsators", IEE Proc. C, Volume-37,(1993)

[22]Gyugyi, L., **"A** unified power flow control concept far flexible AC transmission system", IEE 5th international conference on AC and DC transmission ,(Sept. 1991)

[23]Gyugyi, L., "The unified power flow controller: a new approach to power transmission control", IEEE Trans., Power Deliv.,Volume-10, (1995)

[24] Maheshwari, A., and Ngo, D.T., "Synthesis pulse width modulated waveforms with selective harmonic elimination", IEEE Tram. Power Electron.,Volume-8, (1993)

[25]Makombe, T., An investigation of a unified power flow controller,. PhD thesis, UMIST, UK, 1997

[26]Gyugyin L., Schauder, C.D., Williams, S.L., Rietman, T.R., Torgerson, D.R., Edreis, A., "The Unified Power Controller: Anew approach to Power T transmission Control", IEEE Trans. On Power Delivery, Volume.10, No.2, (April 1995):pp.1085-1097.

[27]Gyugyi, L., "Unified power flow concept for flexible AC transmission systems", IEE Proc-C, Volume-139, No.4, (July 1992):pp.323-332.

[28]Povh, D. Mihalic, R. Papic, I., FACTS equipment for Load Flow in High Voltage Systems, Cigre Symposium, Power Electronics in Power Systems,Tokyo,May 1995.

[29]Mihalic, R, Zunko, P., Povh, D., Modeling of Unified Power Flow Contreoller and its impact on power oscillation damping, Cigre Symposium, Power Electronics in Power Systems, Tokyo, May 1995.

[30]Padiyar,K.R., Power System Dynamics- Stability and Control, John Wiely and Sons (SEA) Pte Ltd, Singapore,1996.

[31]Schauder, C., Mehta, H., "Vector Analysis and Control of Advanced Static Var Compensator ", IEE Proc.-C, Volume.140, No.4, and (July1993):pp.299-306.

[32]Walker, Loren H., "10-MW GTO Converter for Battery Peakin Service", IEEE Trans. on Industry Applications, Volume.26, No.1, (Jan/Feb 1990): pp.63-72.

[33]Padiyr,K.R., Uma Rao, K., “A Control Scheme for Unified Power Flow Controller to improve Stability of Power System” , Paper presented at the 9th National Power Systems Conference, India,Dec.1996.

[34]Gyugyi, L., "A Unified Power Flow Control Concept for Flexible AC Transmission Systems," IEE Proceedings-C, Volume-139, No.4, (July 1992).

[35]Gyugyi, L., "Dynamic Compensation of AC Transmission Lines by Solid-state Synchronous Voltage Sources," IEEE Summer Power Meeting, Volume- 93 July 1993.

[36]Chamia, M., and Angquist, L., "Thyristor-Controlled Series Capacitor Design and Field Tests," EPRI Flexible AC Transmission System (FACTS) Conference, Volume-27, (May 1992) :pp.18-20

[37]Juette, G., "Advanced Series Compensation (ASC) – Main Circuit and Related Components," EPRI Flexible AC Transmission System (FACTS) Conference, Volume-32,(May1992): pp. 18-20