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MODELLING AND CONTROL OF UNIFIED POWER FLOW CONTROLLER FOR REINFORCEMENT OF TRANSMISSION SYSTEMS

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ABSTRACT

The work involved in the thesis is concentrated on modelling and control of UPFC. The overall objective is to provide effective methods and tools for assessing the impact of UPFC in the reinforcement of transmission systems.

The thesis clarifies modelling and control of UPFC into several subproblems, in which the associated models, algorithms and control strategies of UPFC have been systematically reviewed. An electromagnetic transient prototype model of the UPFC has been set up by using its detailed power electronic device as well as its internal closed-loop controller. The problems encountered in the process of building such a model and the way of handling them by EMTP have been discussed. This EMTP-based simulator of SPWM UPFC implemented has provided a useful tool to assist the development and validation of more detailed and practical model of the UPFC for further studies.

The steady-state modelling and control for the UPFC has been developed, including: (i) The power injection model of the UPFC suitable for its implementation in an optimal multiplier power flow computation method has been derived in rectangular form. The effectiveness of the proposed algorithm has been compared with the user defined model method. (ii) A systematic method for deriving the control capabilities of the UPFC has been proposed based on predicting the feasibility limit of the system. Using an index derived from optimal multiplier, three dimensional diagrams describing the ranges have been obtained. The results are also verified through the singular value decomposition algorithm. (iii) A power injection model based control method (PIM) has been proposed and implemented to directly derive the UPFC parameters as so to achieve the control objectives. The assumptions, algorithmic process and validation of the PIM have been investigated in detail. Its pros and cons are also discussed. (iv) Five internal limits of the UPFC device have been derived as the constraints to its performance. A complete set of control rules considering these limits as well as their implementation in the PIM have been constructed to form the basis of optimal UPFC control strategies for its steady-state local control. All the above proposed methods are tested and validated on the IEEE 30-bus system, a practical 306-bus system and a meshed network. The thesis concludes by suggesting the future research areas in further UPFC studies.

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LIST OF SYMBOLS

DC	direct current
AC	alternating current
EHV	extra high voltage
HVDC	high voltage direct current transmission
EMS	energy management system
SCADA	supervision control and data acquisition
AGC	automatic generation control
UK	United Kingdom
REC	Regional Electricity Company
NGC	National Grid Company of UK
GE	General Electricity of USA
AEP	American Electric Power
EPRI	Electric Power Research Institute of USA
EDF	Electricity de France
EUROSTAG	a program of EDF to simulate a unique model of long-term dynamics and transient stability
NETOMAC	Network Torsion Machine Control software of Siemens in Germany
UDPSASP	user defined power system analysis software package of China
SPICE	Simulation Program with Integrated Circuit Emphasis
EMTP	Electromagnetic Transients Program
TACS	Transients Analysis of Control Systems in EMTP
FACTS	flexible ac transmission system
SVC	static var compensator
STATCON	static condenser
NGH-SSR Damper	damper to counter subsynchronous resonance proposed by Dr. N.G.Hingorani
TCSC	thyristor controlled series capacitor
TCPAR	thyristor controlled phase angle regulator
TCSR	thyristor controlled series reactor
UPFC	unified power flow controller

SSSC	static synchronous compensator
SMES	superconducting magnet energy storage
GPFC	generalised power flow controller
MOS	metal-oxide-semiconductor
GTO	gate-turn-off thyristor
BJT	bipolar junction transistor
MCT	MOS-controlled thyristor
FCT	field controlled thyristor
IGBT	insulated gate bipolar transistor
MOSFET	MOS field effect transistor
LTT	light triggered thyristor
SITh	static induction thyristor
PM	proposed method
UDM	user defined model
PWM	pulse-width-modulation
SPWM	sinusoid PWM
VSI	voltage-source inverter
PIM	power injection model based control algorithm
PID	proportional-integral-differential (controller)
PI	proportional-integral (controller)
TNA	Transient Network Analyzer
SVD	singular value decomposition
PCC	point of common coupling
ESCR	effective short circuit ratio
THD	total harmonic distortion
SSR	subsynchronous resonance
GPS	global positioning system
IP	interior point method for solving optimal power flow
T	time or period of fundamental frequency
$T_{\text{turn-on}}$	switching on time of thyristor
$T_{\text{turn-off}}$	switching off time of thyristor
V	voltage magnitude

V_s	magnitude of voltage source at the sending-end
V_R	magnitude of voltage source at the receiving-end
X	reactance or state variables
Z	impedance
I	current magnitude
I_q	current source in shunt part
V_M	mid-point voltage of transmission line
P	active power
Q	reactive power
δ	phase angle
α	phase shift
V_0	busbar voltage at the connection point of shunt part of the UPFC
V_{pq}	series voltage source of the UPFC
V_{sh}	shunt voltage source of the UPFC
V_{dc}	voltage across dc capacitor in the UPFC
$V_{control}$	magnitude of control signal
V_{tri}	amplitude of triangular waveform
f_s	switching frequency
m_a	amplitude modulation ratio
m_f	frequency modulation ratio
T_1	ratio of transformer in the shunt part of the UPFC
T_2	ratio of transformer in the series part of the UPFC
V_{01}	voltage magnitude at fundamental frequency
$k(m_a)$	modulation coefficient of PWM
S	complex power or range space of UPFC parameters
P_{dc}	active power transfer from shunt side to series side
I_{se}	line current through the series inverter
I_{sh}	shunt side current
e	real part of voltage
f	imagine part of voltage or fundamental frequency
μ	optimal multiplier
ω	radian frequency

ϕ	phase angle
Θ	phase angle
$p(t)$	instantaneous power
$v(t)$	instantaneous voltage
$i(t)$	instantaneous current
V_m	peak magnitude of voltage
$P(t)$	average power
a_0	dc offset
$(V_{(i.A0)})_1$	phase voltage of fundamental frequency
f_h	harmonic frequency corresponding to harmonic order h
f_1	fundamental frequency
$f(x)$	a period function
H, N, M, L	element matrixes of Jacobian matrix
$G+jB$	admittance
Δ	incremental value
$P_{i(inj)}$	active power injection at bus i
$Q_{i(inj)}$	reactive power injection at bus i
$P_{j(inj)}$	active power injection at bus j
$Q_{j(inj)}$	reactive power injection at bus j
P_{ij}	active power transfer from busbar i to busbar j
Q_{ij}	reactive power transfer from busbar i to busbar j
Z_{ij}	impedance of transmission line i-j and series transformer of the UPFC
Z_{io}	impedance of shunt transformer of the UPFC
I_{io}	current along with the shunt part of the UPFC
I_{sh}	current source of the shunt part of the UPFC
S_{io}	complex power along with the shunt part of the UPFC
P_{io}	active power along with the shunt part of the UPFC
Q_{io}	reactive power along with the shunt part of the UPFC
N	busbar number of the power system
Goal	cost function of optimal multiplier power flow method
g_0, g_1, g_2, g_3	coefficient for solving optimal multiplier μ
U	control variables

W	output variables of the objectives of control devices
F	system equations
H	functions of control objectives
D	system parameters
J	Jocabian matrix
ε	tolerance of controlled voltage
σ	tolerance of controlled line transfer power
w_{li}	weight factor of line l transfer active power to busbar active power injection at busbar i

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Chapter 1

INTRODUCTION

1.1 Power Systems

1.1.1 Historical Development

Power systems which encompass generation, transmission and distribution of electric energy represent the largest and most expensive man-made system in the 20th century. As a key component of modern society, power systems have been playing an important part in industry, economy and the daily lives of many billions of people. The development of every modern nation very much depends on the energy, electricity, from power systems.

The commercial use of electricity began in the late 1870s when arc lamps were used for lighting house illumination and street lighting. The first complete DC power system (comprising a generator, cable, fuse, meter and loads) was built by Thomas Edison. Afterwards, DC power systems were in widespread use. By 1886 [1], the limitation of DC systems was becoming increasingly apparent. The DC system could deliver power only over a short distance from the generators. To keep transmission power losses and voltage drop to acceptable levels, voltage levels had to be high for long-distance power transmission. Such high voltages were not acceptable for generation and consumption of power, therefore, a convenient means for voltage transmission became a necessity. As a result, AC power systems were inevitably coming up. In 1893, the first three phase AC transmission power at 2,300 V over a distance 12 km was put into operation. By the turn of the century, the AC system had won out the DC system for the following reasons:

(1) Voltage levels can be easily transformed in AC systems, thus providing the flexibility for use of different voltages for generation, transmission and consumption.

(2) AC generators are much simpler than DC generators.

(3) AC motors are much simpler and cheaper than DC motors.

In the early period of AC power transmission, frequency was not standardised. Many different frequencies were in use. In the UK, frequencies were standardised by the Act of Parliament in 1926 to 50 Hz, a frequency deemed just enough for flicker of electric lights to be unnoticeable. The increasing need for transmission of large amounts of power over longer distance created an incentive to use progressively higher voltage levels. In some countries, higher transmission voltage up to 765 kV (EHV) is used. To avoid the proliferation of an unlimited number of voltages, the industry has standardised voltage levels. For instance, the standards in the UK are 132 kV, 275 kV and 400 kV.

A tendency in the history of AC power systems is the interconnection of neighbouring utilities, referring to 'grid system'. The main advantages of the grid system were:

(1) A failure of one generating station did not threaten the electricity supply of an area.

(2) Electricity could now reach rural areas.

(3) Electricity became more economic because many of the interconnected generating stations could be shut down overnight, when demand was low, leaving only a few stations to supply the load.

Furthermore, in order to cope with the ever increasing demand for electrical power, the grid system with higher voltage levels and coexisting HVDC transmission continues to grow.

1.1.2 Functional Structure

In practice, power systems operate at various voltage levels separated by transformers. From voltage-level point of view, a power transmission network can be classified into the following subsystems and shown in Figure 1-1.

(1) Transmission system

(2) Subtransmission system

(3) Distribution system

The transmission system interconnects all major generation stations and main load centres in the system. It operates at the highest voltage level (typically, 230 kV and above) and handles large amount of power. Via inter-ties, transport of power can take place to or from other power systems belonging to the same power pool.

The subtransmission system transmits smaller amount of power from transmission substations to distribution substations. Large industry customers are served directly by the subtransmission system. Typically, voltage varies between 11 kV and 132 kV.

The distribution system represents the final stage in the transfer of power to the individual customers. The primary distribution voltage is typically between 4 kV and 34.5 kV. Small industrial customers are supplied by primary feeders at this voltage level. The second distribution feeders supply residential and commercial at 120/240 V.

In the electricity grid of UK covering England and Wales, there are over 200 substations at 400 kV and 275 kV, 7,000 km overhead transmission line routes and 600 km of cable, roughly 11,000 switches and circuit breakers and numerous items of protection equipment and a peak demand of about 50GW. It comprises of the Generating Companies, a Transmission Company - the National Grid Company - and the Regional Electricity Companies (RECs). In England and Wales the four biggest generating companies are National Power, PowerGen, Magnox Electric and Nuclear Electric who are responsible for the majority of generated electrical power. In addition, private generating companies are now allowed to supply power on a commercial basis. At present these generators are small compared to the capacities of the big 4, however, competition may change this situation in the future. Additionally, England is connected to Scotland via AC links and France via a DC, submarine, cross-channel link. This DC link has the ability to transfer up to 2,000 MW in either direction.

The National Grid Company is responsible for conveying bulk power from areas of generation to areas of consumption. This process is referred to as the aforementioned term transmission. In addition, the NGC is responsible for co-ordinating all major power stations on its system and is entrusted to ensure the sufficient electrical power is available to meet any expected demand at the lowest cost to the customer. The RECs are responsible for conveying power from the nearest NGC supply point to the customer. This business is referred to as distribution.

Obviously, modern power systems consist of multiple generating sources and several layers of transmission/distribution networks. This provides a high degree of structural redundancy that enables the system withstand unusual contingencies without service disruption to the customers. On the other hand, as power systems increasingly expand, the result is a very large system of enormous complexity. Therefore, the design of such a system and its secure operation are indeed a challenging problem.

1.2 Power System Operation and Control

1.2.1 States, Phenomena and Models

For the purposes of analysing power systems and designing appropriate control systems, it is helpful to conceptually classify the system operating conditions into three main states: electromagnetic transient state, electromechanical transient state and steady-state.

Characterisation of the system conditions into the three states provides a framework in which modelling and control strategies of power systems can be developed and operator actions identified to deal effectively with each state [2, 3]. However, this classification is made in the view point of system states. From the view point of study models, these states are strongly associated with different phenomena in terms of time. It is necessary to understand thoroughly and to quantify, with the required accuracy, the phenomena which affect the electrical system. This is the role of power system studies, which cover a wide range of time constants. Figure 1-2 illustrates the relative positions of the phenomena and the main types of models: it will be noted that one tool is not exactly adequate for the problems and that a problem such as the interaction between AC transmission system and HVDC systems, extending over practically all the time-scales, must be analysed by two or three different models. Therefore, power system studies often focus on three fundamental models: Electromagnetic transients, Stability (including Long-term dynamics) and Steady-state. These models can be used separately or combined to investigate the phenomena associated with the relevant three states of the power system.

(1) Electromagnetic transients in which the dimensions of the components of the power system are no longer negligible compared to the wavelength of the propagation phenomena.

For high speed phenomena, current and voltage waves can no longer be considered as sine waves at 50 Hz or 60 Hz with slow amplitude modulation. As an illustration, phenomena appearing on the system which, on account of their highly non-linear nature or their extended frequency spectrum, require detailed representation of the dynamics of the electrical system, including lightning waves which appear following a lightning strike on one or more conductors of a line, or an overhead earth wire, or the ground close to a line. The propagation of the resulting waves calls for a representation of the lines, towers, surge impedance of the earth connections derived directly from Maxwell's equations, and modelling of the non-linear lateral losses in the dielectric (corona effect). The modelling of the air gap and the surge impedance of the tower can also be required if one wishes to simulate back flashover, which gives rise to waves of a steeper form than the lightning wave itself. To obtain an idea of the form of the lightning wave, it is sufficient to know that this is synthesised in the laboratory as a bi-exponential wave with a rise time of 1.2 μs and a decay time of 50 μs.

(2) Electromechanical stability

The concept of electromechanical stability is derived from the viewpoint of mathematics expressions of power systems. In fact, the whole process of this type of stability may have different forms, and thus the electromechanical stability can be divided into different aspects as follows:

(i) Stability corresponding to the electromechanical oscillations of machines, and the action of primary voltage and speed controls.

This concerns phenomena with a time constant between approximately 0.1 s and 10 s. The simulation of these will consider as instantaneous the high speed phenomena (time constant<0.10 s) such as transients inherent in the power system. Slow variables (time constant>10 s), such as certain parameters of steam generators, will be considered as constant.

Classically, two major classes of stability phenomena are distinguished:

(a) Transient stability: this corresponds to large amplitude movements of machines during sudden disturbances, for example a short-circuit, causing considerable imbalance between the driving torque and the opposing torque.

(b) Small signal stability: this corresponds to the normal operating conditions of the power system in the presence of normal low amplitude fluctuations of electrical or mechanical variables.

The system is stable if it retains or resumes a position of equilibrium where all the machines are in synchronism.

The range of frequencies involved extends from a few tenths of hertz (0.2~0.3) to a few hertz (5~6). In this frequency band, it is the machines which determine the dynamic behaviour of the system, so they must be represented in detail.

(ii) Long-term dynamics corresponding to normal changing patterns of loads and the action of some automatic controls.

Essentially this involves analysis of the behaviour of the voltage and maintaining the balance between generation and consumption, that is, control of the frequency and power flows on interconnections. For this purpose, it is necessary to monitor the changing pattern of different electrical or mechanical variables with time, over several minutes, tens of minutes or even several hours.

The simplest model which might be suitable would involve calculating active and reactive power flows after each change in the topology of the network, the power generated and the consumption.

However, such model does not take into account slow transient phenomena. A correct state can be found although, taking into account time constants, thresholds and response delay times of the various elements of the system, one would observe transient states on the actual power system which could cause the equipment to react, changing the evolution of the system accordingly, such as:

(a) overload tripping of elements;

(b) load shedding or islanding when frequency falls;

(c) tripping out of generating sets by auxiliary protections based on voltage or frequency drop.

Therefore, the long term dynamics model brings a great improvement in the calculation of the frequency, reflecting the dynamic balance between generation and consumption. The power flow calculation equations concerning the network are added by differential equations representing the dynamic operation of the turbine and boiler generating assemblies, mechanical equations for shaft lines and local or centralised controls which interact with the phenomena simulated.

(3) Steady sate conditions in which all the variables and parameters are assumed to be constant during the period of observation: power distribution, sustained short-circuit current, etc..

The steady state of a power system at a given moment is used either to examine if the generation and transmission capacities are adapted to the demand in a given situation, or to have a starting point (initial state) for transient state simulations. The problem that to be solved is that of determining the steady state power flow through the different transmission system components, or more generally, that of calculating the voltage magnitudes and the voltage phase angles at all the system nodes. In this framework, a simplified modelling has been adopted through which the whole generation-transmission-consumption system can be rapidly simulated.

The first main simplification consists in considering only the electric variables with an angular frequency ω corresponding to the fundamental frequency which will vary only slightly from the nominal frequency (50 Hz or 60 Hz). Fast transient phenomena are thus not dealt with, and the time constants in the transmission lines (a few tens of milliseconds), in the transformers and in the generators (a few hundreds of milliseconds) are so low that they can be neglected. No component of the power system will therefore be modelled using a differential equation. Current, voltages, powers, and impedance are thus expressed as complex variables in polar co-ordinate or Cartesian co-ordinate (rectangular co-ordinate).

The second simplification consists in limiting the study to equivalent single-phase circuits which correspond either to the balanced states of a three-phase network, or to the positive, negative or zero sequence components of the unbalanced states. This assumption implies the existence of a triangular symmetry for the three phases of the power system components.

Based on the above assumptions, the steady state models of a power system can be readily derived and used to investigate the related problems.

1.2.2 Impacts of Computer and Communication Technologies on Power Systems

The fundamental objectives of an electric energy system are to supply electric energy to the various loads throughout a given service area. Properly designed and operated, it should meet the following requirements:

(1) It must supply energy practically anywhere the customer demands.

(2) The load demands for real and reactive power vary with time. The system must be able to supply this ever-changing demand.

(3) The delivered energy must meet certain minimum requirements with regard to quality which refers to: constant frequency, constant voltage, and high reliability.

(4) It should deliver energy at minimum economic and ecological costs.

In order to achieve these objectives and effectively manage the power system, operators must be aided with some advanced means to understand the real-time developing trends of power systems. Nowadays, with the advent of computers and communication means, an open control structure system - Energy Management System (EMS) - has been rapidly developed. With the help of EMS, the operators acquire the system information much more and faster than ever, in which the computer takes the task of collecting, processing, distributing real-time data and communication means undertake the role of transferring these information. EMS focuses on the new technology development of computers and communication applicable to power systems, which brings a great evolution of modern power system operation and management. Typically, an EMS will provide the following functions:

(1) Supervisory control and data acquisition (SCADA)

(2) State Estimation

(3) Automatic generation Control (AGC)

(4) Security assessment

(5) Load forecasting and unit commitment

(6) Reactive power dispatch

1.3 Commercial and Technological Challenges

Although there are wide applications of modern computers and communication means in power systems which can provide a better framework to modern power systems, it still lacks some effective fundamental control means for transmission lines to match the high-speed digital system of EMS. As is well known, EMS behaves like a nerve-centre and has the ability to convey the information to the executive mechanism. However, advanced technology involving the executive equipment is still developing as to achieve the whole integrated system objective effectively. Furthermore, the global privatisation and marketing of electrical energy systems calls for much more complex and flexible control structures in order to make full use of electricity and to achieve the maximum efficiency.

1.3.1 Market Driven Incentives for New Control Means

Power system planners and operators are becoming increasingly aware of the limitations imposed on electric transmission networks. The present situation in many countries of the world is characterised by the following trends [4, 5]:

(1) Increase in consumption of electrical power

In developing countries, there is a rapidly rising demand for electricity created by industrialisation and urbanisation coupled to population increase. In industrialised countries the electricity fraction of the total energy consumption is also increasing, because electricity is important for productivity increase and for environmental control. Also electricity is regarded as superior for the purpose of most users.

(2) Growing public concern

Paradoxically, although electricity is being increasingly used, there is a concern on the part of the general public of the impact of new transmission facilities. Biological effects of electrical magnetic fields are being discussed and investigated. In this process science and technology have become ever more politicised.

(3) Regulatory constraints

Obtaining Right-of-Way and licenses for construction of new transmission lines is becoming increasingly difficult and time consuming. The Not-in-My-Backyard attitude of the general public coupled with regulatory and financial constraints has also contributed to a slowdown in capacity growth of new generation, particularly large base-load units.

(4) Operational constraints

In many places around the world, the restriction imposed on the addition of new facilities has led to decreasing operating margins. Also the "free flow" mode of power across transmission facilities results often low capacity usage of many lines due to uneven sharing of power flow between parallel lines and/or in loop power flows in interconnected transmission systems.

The above cited examples are indeed sufficient for one to realise what the power system market needs are now and how they will develop in the future. For example, the electric transmission systems represent a vast accumulated economic value, and it makes good sense to try to direct efforts in the following general directions:

(a) Improved utilisation of existing facilities

In this aspect, an increase in power transfer capability in existing transmission corridors would be very beneficial. The economic advantage offered by deferring large and difficult investments in new facilities is also obvious. Another way to improve the utilisation of the power system would be to reduce losses.

(b) Improved transmission system flexibility

Being able to suitably adapt to changing operating conditions and to varied network configurations certainly help the utilities in maintaining reliable service to their customers, particularly during and subsequent to network disturbances and contingencies.

By analysing the above mentioned transmission market environment and needs, one can draw the conclusion that the market will require new solutions in transmission systems. For example, for transmission system in the future, they will operate in a ”controlled power flow mode” under the definition of ”contract path” as opposed to the present free flow mode of operation. This would enable the utilities not only to optimise point-to-point power transfer, safety margin, losses, etc., but also to open up new possibilities for electrical energy trade. In short, one would capitalise on potential economic benefits in the steady state operation of the transmission system. Under dynamic conditions, and if adequate response times are provided for in the ”controlled power flow mode” of operation, improved response to facility outages, damping of power oscillations and better voltage stability can be achieved.

1.3.2 Technology Driven Incentives for New Control Means

The advances made in power semi-conductor technology, featuring the development of high-voltage/high-current thyristors, directly light-triggered self-protected thyristors and their successful application in High Voltage Direct Current systems and Static Var Compensators have demonstrated the technical and economical viability of power semi-conductors in the transmission field. In recent years, Gate-Turn-Off thyristors (GTO) have been made available, and research is going on aiming at a refinement and improvement of components turn-off capabilities [6].

With this technological background in mind, one can see many opportunities of the development of so-called force-commutated converters, a family of equipment that can perform the required function in a given application. Examining the basic equations for active and reactive power transmission across a line, the following functions are required in order to achieve power control and flexibility of operation:

(1) Line impedance control

The apparent line impedance can be varied if a voltage of controlled magnitude and phase angle can be inserted in series with the line. This function can be performed by a force-commutated converter. For a predetermined value of equivalent impedance, the output voltage of the converter must be controlled by the line current. There are also heavy-duty mechanical coupler, breaker or thyristor switched series capacitor modules, that can yield a more direct line impedance control.

(2) Phase angle control of busbar voltage

Here again, phase shifting of a given bus voltage can be achieved using a force-commutated converter that adds a voltage of controlled magnitude and angle in series with the line. For a predetermined value of phase shift, the output voltage of the converter must be controlled by the bus voltage. There are, of course, other alternatives offered by the traditional (transformer based) fixed, tap-changer operated or thyristor switched phase shifter.

(3) Amplitude control of bus voltage

The well established Static Var Compensator concept already performs this function, using conventional thyristor technology. A force-commutated converter connected in shunt with the line can also perform the same function.

It can be observed from the above mentioned facts that in the traditional technology, impedance is directly related to series capacitors while phase angle control is directly related to transformers. So, the technology driven approach has given hints on how the goals of flexibility can be achieved. However, it has not yet given a clear indication of why a certain technology should be selected (performance, cost, reliability, etc.) nor when these concepts can be successfully implemented.

1.4 Development of Supplementary Devices to Reinforce Power Systems

1.4.1 Development of Conventional Control Devices for Power Systems

In fact, as early as 1920's, the concepts of using series capacitors and shunt capacitors to control line power flow and busbar voltage were derived from fundamental equations of power flow transfer. Since then, many efforts have been made to help to solve some of power flow and capacity problems arising from the transmission access issue, and help to provide reliable quality power to future customers. The results of efforts are the mechanically controlled means, such as the mechanically controlled phase shifter and shunt capacitors. However, these mechanical means can not overcome some constraints while maintaining the required system reliability. For example, often a 500 kV line, may have an operating limit of 1,000 -1,500 MW compared to a thermal limit of 3,000 MW. These mechanically controlled equipment can not enable such a line to carry power closer to its thermal rating. Although mechanical controllers are less expensive, they need to be supplemented increasingly by rapid-response power electronics controllers.

The power systems of today, by and large, are mechanically controlled. Most of the electronics and high-speed communication in present transmission systems are equipped locally, however, when operating signals are sent to the power circuits, where the final control action is taken, the switching devices are mechanical and there is little high-speed control. Another problem with mechanical devices is that control cannot be initiated frequently, because these mechanical devices tend to wear out quickly compared to static devices. In effect, from both a dynamic and steady-state point of view, the system is really uncontrolled. Power systems planners, operators and engineers have learned to live with this limitation by using a variety of ingenious techniques to make the system work effectively, but at a price of allowing significant inefficiencies, greater operating margins, and redundancies. However, these problems can be effectively solved with the advent of new technology - HVDC, FACTS (flexible ac transmission systems), and CUSTOM POWER.

1.4.2 HVDC, FACTS and CUSTOM POWER

Power systems are at the beginning of an era of significant change - an era that is technology and market driven by microelectronics (computers and micoprocessors), communications, and power electronics. The combined impact of these technologies makes the era unique and important for both transmission and distribution, by making them more reliable, controllable, and efficient.

- HVDC (High-Voltage Direct Current transmission) - the thyristor-based technology thrives on the need for highly reliable power transfer across natural or national boundaries [7, 8, 9].

- FACTS (Flexible Alternate Current Transmission Systems) - the use of high-power electronics to enhance the controllability and capacity of utility transmission systems [10].

- CUSTOM POWER - customised electric service for industrial and commercial customers through the application of power electronics on utility distribution networks [11].

These thrusts are designed to overcome the limitation of the present, mechanically controlled ac transmission systems. By using reliable, high-speed power electronic controllers, they offer the following principal opportunities to the power systems:

(1) Control power so that it flows on the prescribed transmission routes.

(2) Allow secure loading of transmission lines to their thermal limits, while avoiding overloading.

(3) Reduce generation margins through increased usable transmission capacity.

(4) Prevent cascading outages by limiting the impact of faults and equipment failure.

There opportunities arise through the ability of these controllers to control the interrelated parameters that constrain today's power systems, including series impedance, shunt impedance, phase angle, and the occurrence of oscillations at various frequencies below the rated frequency. As well known, HVDC technology has been widely used in all over the world and its mature and successful manufacture and operation experience provides the solid foundation for promotions of FACTS and CUSTOM POWER. As these three technologies belong to different research fields, the main theme in this thesis will focus on the studies of FACTS device applications in transmission systems. FACTS technology includes many different types of equipment, such as Static Var Compensator (SVC), Damper to counter subsynchronous resonance proposed by Dr. N.G.Hingorni (NGH-SSR Damper), Thyristor-Controlled Series Capacitor (TCSC), Static Condenser, Thyristor Controlled Phase Angle Regulator (TCPAR), Current Flow Controller, Dynamic Voltage Limiter, Thyristor Controlled Series Reactor (TCSR) and Unified Power Flow Controller (UPFC), etc. The UPFC - a typical representation of FACTS technology owing to its multiply functions of simultaneous, real-time control of all basic power system parameters (transmission voltage, impedance, and phase angle) or any combinations - has been selected as the study candidate in the thesis.

1.4.3 The UPFC

The UPFC [12], is a sort of 'complete' controller, one in which an ac voltage vector of a variable magnitude and phase angle, generated by a thyristor based inverter is injected in series with the phase voltage. When the injected voltage is not in quadrature with the current, the inverter has to inject both active and reactive power. The active power supplied from a dc link in which driving dc voltage for the inverter is obtained by rectifying the ac to dc from the same transmission line. Because, in such an arrangement, the injected voltage can have any phase angle relationship to the phase voltage, it allows precise control of both active and reactive power.

The practical realisation of the UPFC requires a solid-state ac to ac converter, which can be implemented by two similar voltage-source inverters operated from a common dc link capacitor. Recent advantages in high-power semiconductor technology have resulted in gate turn-off (GTO) thyristors of sufficient ratings for high-power utility applications. Using GTO, the UPFC results in a uniform hardware approach to power flow control as the constituent inverters are identical to those employed in the advanced SVC and controlled series compensator schemes. It is this significant benefit of the UPFC multiply control functions that pushes this research project forward.

1.5 Research and Development of UPFC

1.5.1 Issues to be Addressed in UPFC Applications

Having multiple functions, the UPFC can play an important role in solving transmission system problems, such as supporting voltages and controlling power transfers under steady-sate, enhancing system damping and improving transient stability margins. There are three issues [13, 14, 15, 16] which need to be carefully addressed with the applications of UPFC in reinforcement of transmission systems. They are:

- Determine the UPFC placement and its size and rating
- Determine UPFC's control strategies in different states
- Determine UPFC's protection, operation and co-ordination with other devices in the system

In order to facilitate the above studies, the first step is to set up UPFC models for three different operation states, then to implement them in the associated algorithms or tools, and finally to design control strategies [17, 18, 19, 20]. Fundamentally, these involve the following two tasks:

(1) Modelling

In this aspect, the UPFC models should cover three states: electromagnetic transient state, steady-state, electromechanical transient state. These models are not only needed to include the important features of the UPFC relating to the relevant state, but also are flexible and compatible enough to be incorporated in currently existing algorithms and software. As the UPFC is represented by various models in different states, the ways of dealing with them are also different. These works involve knowledge of power electronics, power flow and stability computation and computer simulations.

(2) Control

For optimally operating the UPFC, the development of control strategy for UPFC is the key. The control structure should include global central controller, local controller and internal controller. The design of these controllers is associated with different UPFC models, various control objectives and control schemes, as well as different simulation methods and the system scale. These methods should be integrated in order for the UPFCs to be formed as a continuous closed-loop control in different states.

1.5.2 Requirements of Modelling and Control of UPFC

1.5.2.1 From the Viewpoint of Modelling

In general, modelling of the UPFC [21, 22, 23] is a fundamental step for any UPFC related studies. The follows are some problems that we need to take into account when we model the UPFC:

(1) Models of the UPFC should cover three main states of power system operations. Once the UPFC is installed in the system, it will experience all processes of power system operations, including three main states: electromagnetic transient state, steady-state and electromechanical transient state. Some phenomena associated with these states occur in terms of different time scales. It is these time scales which make the UPFC's model different in various states. In fact, the UPFC model under the electromagnetic transient state should consider all factors such as physical arrangement and protections of the device in a detailed level. While the steady-state and electromechanical transient state UPFC model both can be mathematically derived from its electromagnetic transient state model under different assumptions and simplifications. It is important to notice that the UPFC models under three states may appear in various forms.

(2) Models of the UPFC should contain main features of the real-world UPFC. Whatever the models of UPFC appear under different states, they should reflect the main characteristics of the UPFC. Firstly, the models representing the UPFC should be consistent with the operation concept of the device and match relevant physical arrangements. Secondly, the state variables selected from the model should satisfy the internal conditions of the UPFC and the external constraints to the system. Finally, all these state variables should be visible and have physical meanings which are helpful for engineers to better understand the UPFC.

(3) Models of the UPFC should be consistent in terms of viewpoint of the system. As the UPFC is a complete device, its operation is continuous without a great interrupt. So, models of different states also should have such feature, which means that different models inherit each other and are compatible.

(4) Models of the UPFC are flexible and readily changeable to suit the associated algorithms adopted. Before the model of the UPFC is determined, it should be taken into consideration its flexibility and possibility to be implemented in existing tools or algorithms, although it sometimes needs to be transformed into the form demanded by the algorithm.

(5) The algorithms should be thoroughly investigated ranging from algorithm convergence, computing time as well as whether they are suitable for control strategies to be incorporated. All these factors affect the algorithm efficiency. Some algorithms may be too slow to operate.

(6) The software thus developed by combining the UPFC with the associated algorithm should follow the trend of software development such as Objected Oriented Program, User Defined Model and friendly user interface.

(7) Making full use of these UPFCs models and their algorithms, we can deal with many fundamental problems concerning the UPFC applications and its impacts on power systems. For example, open-loop simulations of these models can help planners and operators to determine the UPFCs operating ranges and justify their impacts on the system, thus inspiring ideas to better control UPFCs. They are often used to validate control strategies of the UPFCs.

1.5.2.2 From the Viewpoint of Control

Control is the key of the UPFC. The concept of the UPFC is that it has ability to concurrently control voltage and transmission line power flow [24, 25, 26, 27, 28]. Therefore, designing control strategies for the UPFC under different states is necessary to realise its functions. Here, some factors affecting control strategies of the UPFC are presented:

(1) Clarify control objectives under different states. For different states, the system may produce various unexpected phenomena which the UPFC is demanded to eliminate. For example, voltage and power flow control are main aims under steady-state operation while eliminating oscillations is the goal of electromechanical dynamic state. Thus, a certain control objective must be first defined for a certain phenomenon corresponding to the relevant state. Only is the control objective clarified and then the associated control design method can be correctly applied.

(2) Clarify central and local schemes. As is well known, the control objective of the UPFC can either be global or local and thus leads to different methods. This is because the UPFCs are needed to co-operate from the point of view of central control. While local control emphasises on control of partial areas. The great difference between them is that the former considers global co-operations of all UPFCs as well as other control devices in the system and the latter only takes individual control behaviour into account.

(3) Choose right input signals to control schemes. As the control objective is clarified into global, local and different states, it is very important to understand what kind of signals can be obtained and used to achieve the defined objective. Those signals as the input of control strategy can be of different types, whether having physical meanings or being fictitiously made. Generally, they should be obtained quickly enough to match the fast control speed of the UPFC. This may be well done by local control because it sometimes does not need remote signals. However, for the global control strategy or some local controller, it usually has remote signals first and then feeds output signals back remote UPFCs. This process is definitely time consuming which ruins efficiencies of the UPFCs and the global control strategy. Therefore, choice of input signals is made in terms of practical operations.

(4) Adopt advanced control technology. With rapid development of modern control theory, the UPFC has more wide choices for its control scheme. Any control theory, such as conventional PID control or modern optimal control, neural network, fuzzy logical control can be applied. Some concepts such as sensitivity, decoupled, linearized and non-linear may be involved.

(5) Validate control strategies. Once the control strategy is derived, the best way of testing it is put it into practice. However, this is not feasible. An alternative method of validating it is off-line simulation technology. Another better way is the combined digital-analogue test such as TNA equipment (Transient Network Analyzer). Here, the off-line simulation focuses on pure digital analysis. Therefore, some particular methods can be used to test effectiveness of control strategies. For example, eigenvalue methods and minimum singularity value methods may be used to validate the control strategy of the UPFC under small signal stability. Time-domain simulation methods can prove the control strategy under electromechanical transient state.

1.5.3 Current Developments in Modelling and Control of UPFC

Since it was proposed in 1992, the UPFC has received much attention and has been under implementation for a practical system. Many papers have been published which have covered many aspects of UPFC research. [29] and [30] set up electromagnetic state UPFC model and simulated them using EMTP simulator. [31, 32] described steady-state models of UPFC in terms of two voltage-source representations and then implemented the models in the Newton-Raphson power flow algorithm. [33, 34, 35] used different commercial software to simulate steady-state UPFC model by using the provided user defined model. [36] derived some operation limits of UPFC, which constrained the maximum power transfer regulated by UPFC. [37] presented a dynamic model of UPFC and carried out eigenvalue analysis. Furthermore, [38] discussed the capabilities of UPFC and [39] introduced UPFC in voltage stability studies.

However, it seems to the author that few contributions in the literature systematically addressed the modelling, algorithms and control strategies for UPFC from a system point of view. Many of the papers mentioned treated the UPFC from the experiences gained from other FACTS devices without considering its unique characteristics. Secondly, most work done so far is based on the conceptual model of the UPFC. The proposed control strategies for UPFC are mainly for stability type problems. Thus it is clear that there is a great demand to address the modelling and control aspect of UPFC in a more detailed and systematic way.

1.6 Scope of This Thesis

In order to evaluate the impact of UPFC on transmission systems, the following three important aspects associated with UPFC applications have been addressed in the thesis:

(1) Modelling: How is the UPFC modelled particularly in electromagnetic transient state and steady-state?

(2) Algorithm: What kind of algorithms or tools should be employed to incorporate the above models?

(3) Control: How are the UPFC's parameters determined to achieve the system objectives?

It is these three problems that forms the research theme of this thesis. Or in more detail, the following summarise the objectives of the research into these three aspects:

Developing the UPFC model based on the voltage-sourced inverter employing the GTO power electronic devices ; Realising the generation of PWM signals and design of internal closed-loop controller of the UPFC which can be readily changed according to the control demand; Using functions provided by EMTP to undertake the detail studies of the UPFC under harmonics, open-loop control and closed-loop control so as to deeply understand the interactions between the UPFC and the system.

Modelling the steady-state UPFC by employing the power injection model; Implementing this model in the optimal multiplier power flow algorithm in terms of rectangular forms; Investigating the convergence of the proposed algorithm and comparing it with the widely-used, user defined model, method; Proposing the optimal multiplier as an index to obtain the UPFC maximum control capabilities based on predicting the system feasibility limit; Studying the power system performance with the UPFCs.

Proposing a novel control strategy - power injection model based control algorithm (PIM) - of determining the UPFC parameters so as to achieve the control objectives and providing insight into the factors affecting the proposed control method; Presenting a new controller constrained by the UPFC internal limits which forms the complete control strategy of the UPFC along with the PIM.

1.7 Contributions of the Thesis

(1) The development of FACTS controllers associated with power electronic devices has been systematically reviewed.

(2) The problems of applying the UPFC in power systems have been clarified, including modelling, algorithms and control strategies as well as their relationships in different time scales ranging from electromagnetic transient state, steady-state to transient state.

(3) An electromagnetic transient prototype model of the UPFC has been set up by using its detailed power electronic device as well as its internal closed-loop controller. The problems encountered in the process of building such a model and the way of handling them by EMTP have been discussed. This prototype model has realised the functions and can be extended to many other types of FACTS devices.

(4) The power injection model of the steady-state UPFC suitable for its implementation in an optimal multiplier power flow computation method has been adopted in rectangular forms. Simulation results have been obtained on IEEE benchmark model system and a practical system. The effectiveness of the proposed algorithm has been compared with the user defined model method.

(5) A systematic method for deriving the control capabilities of the UPFC has been proposed based on predicting the feasibility limit of the system. Using an index derived from optimal multiplier, three dimensional diagrams describing the ranges have been obtained on an IEEE test system. The results are also verified through the singular value decomposition (SVD) algorithm.

(6) A power injection model based control method (PIM) has been proposed and implemented to directly derive the UPFC parameters as so to achieve the control objectives. The assumptions, algorithmic process and validation of the PIM have been investigated in detail. Its pros and cons are also discussed.

(7) Five internal limits of the UPFC device have been derived as the constraints to its performances. A complete set of control rules considering these limits as well as their implementation in the PIM have been constructed to form the basis of optimal UPFC control strategies for its steady-state local control. Various simulation studies have been conducted under these rules.

(8) The future work of the UPFC research as well as the most recent development of the UPFC applications has been discussed.

1.8 Thesis Layout

Chapter 2 reviews the development of power electronic devices, FACTS and the UPFC. It describes some applications of FACTS and the UPFC in practical power systems.

Chapter 3 first introduces the operation theory of UPFC in transmission systems. Then, various models, algorithms and the control strategies of the UPFC are reviewed.

Chapter 4 describes the way of setting up the electromagnetic transient model of the UPFC using the physical circuit prototype. EMTP/TACS has been used to simulate the interaction between the UPFC and the system. The aim of the chapter covers harmonics, open-loop operation and closed-loop control of the UPFC.

Chapter 5 derives and implements the power injection model of the steady-state UPFC so as to meet the demand of the power flow algorithm. The deficiencies of the conventional power flow methods to incorporate the UPFC model has been studied. The chapter gives the test results of the algorithm on IEEE-30 bus system and a practical 306 bus system, which also include the comparison with the user defined model method.

Chapter 6 presents a novel and direct method to obtain the maximum operating range of the UPFC based on predicting the system feasibility. The optimal multiplier in the normal power flow computation has been employed as the indicator to forecast the power flow convergence.

Chapter 7 proposes a new control strategy to directly determine the parameters of the UPFC to meet the required control objectives. The method is called power injection model (PIM) based control algorithm, whose convergence, performance and impacts on the system have been investigated in detail. The PIM has been tested on a meshed system derived from a large scale system.

Chapter 8 describes the five internal limits of the UPFC at first. These limits are then transformed into a set of control rules as to constrain the control and operation of the UPFC. The proposed control strategies and their implementation in PIM form a complete local controller of the UPFC.

Chapter 9 summarises main conclusions of the thesis and points out future work in application and research of the UPFC.

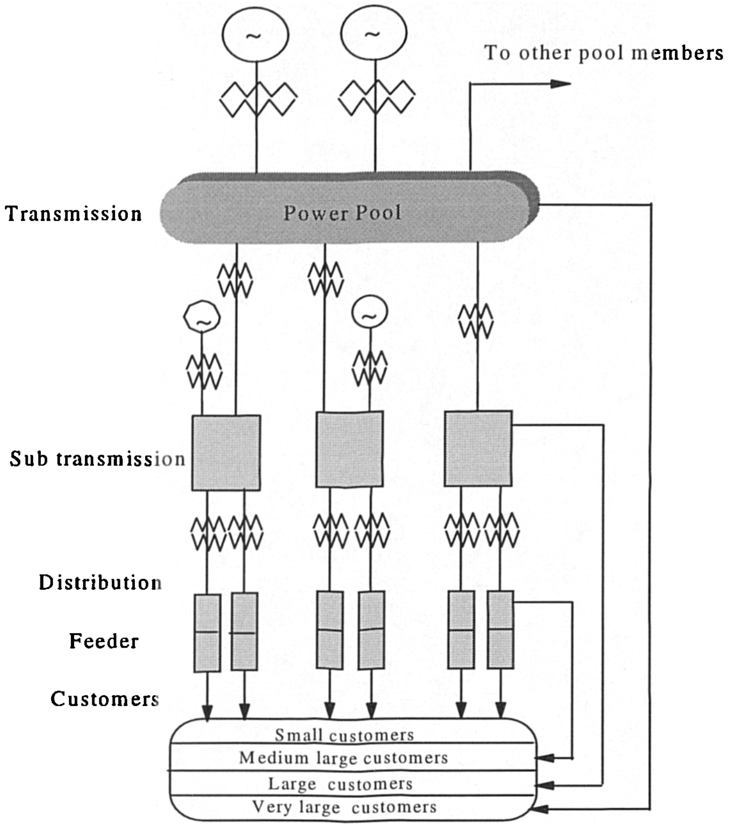


Figure 1-1 Power system structure

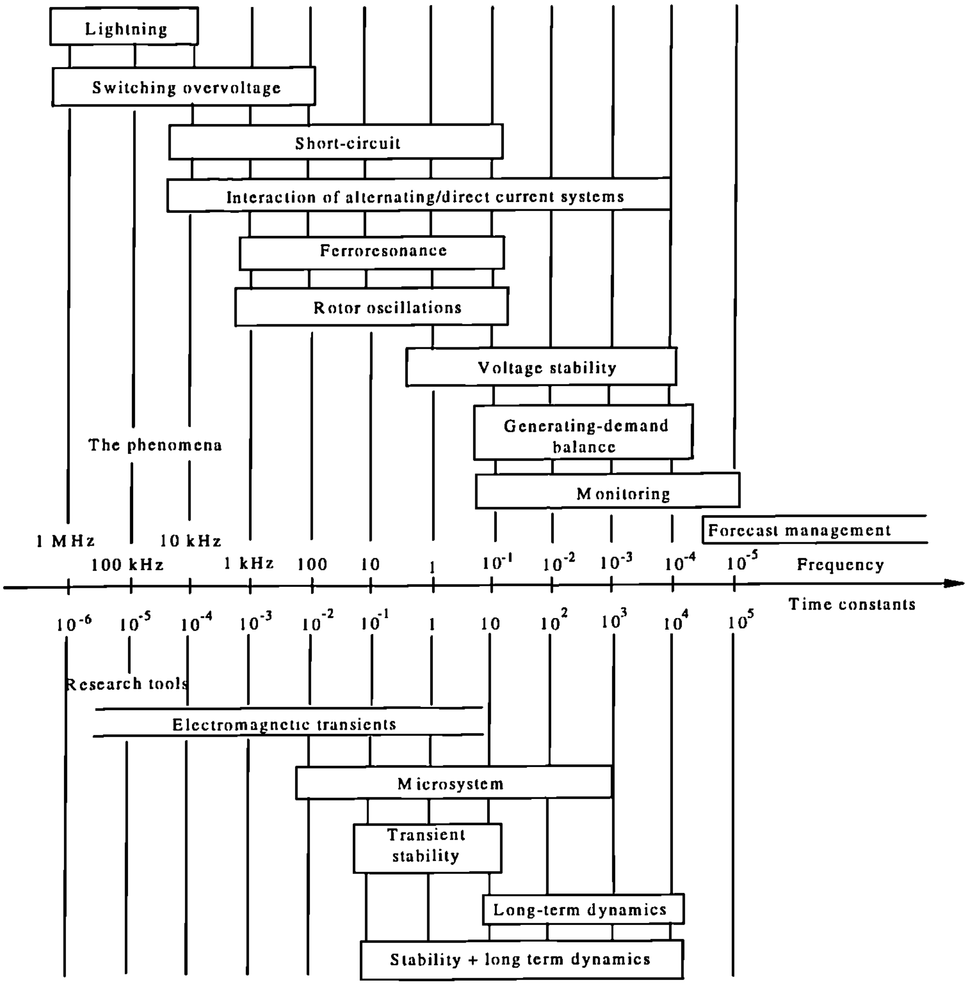


Figure 1-2 The time-scales of phenomena and the main tools [3]

Chapter 2

FACTS - POWER ELECTRONICS APPLICATIONS IN AC TRANSMISSION SYSTEMS

2.1 Introduction

The use of power semiconductor devices in the transmission of electrical power has been well established and is growing rapidly. HVDC transmission is an established technology for which thyristors have become the workhorse since the installation of the first solid state converter at Eel River in 1972. FACTS and CUSTOM POWER technologies can be utilised respectively to improve the utilisation of ac networks and the quality of the supply of ac power. Developments in each of these application areas are conditioned heavily by advances in power semiconductor devices, whether latching (e.g. thyristors) or fully controlled. In the latter case there are a number of candidate devices. The objective of this chapter is to review and outline the attributes of the various modern power electronic devices to help to assess their potential applications in electrical power transmission networks. Furthermore, the fundamental theory of transmission systems associated with FACTS applications will be explained. Some representative applications of FACTS devices in practical systems will be illustrated to show advantages and benefits of power electronics based FACTS technology.

2.2 Development of Power Electronics and Its Applications

2.2.1 Devices and Characteristics

A diversity of device types is now available to designers of power electronics equipment [40, 41, 42, 43], as illustrated in Figure 2-1, where the device types are conveniently classified into two groups: (i) latching devices which require circuit commutation to extinguish current, and (ii) bimodal devices in which current flow can be initiated and extinguished by gate control. Device evolution has been driven by customer demand from the power transmission and rail transportation industries. The demand has been for higher device power ratings and for faster switching, whilst the evolution has been enabled by the availability of larger diameter silicon and by MOS technology of progressively finer detail developed for the integrated circuit industry. Thus, in the space of 30 years, silicon wafer diameters have increased by about six times to the present 150 mm, and in less than 20 years the cell size of power MOS structure has correspondingly reduced to less than 10 μm today. Also shown Figure 2-1 is the approximate year of emergence at a usable power level of each device type and its ranking according to its on-state voltage drop when fully conducting at its average current rating. This current level depends on the area of silicon used in fabricating the device. The dashes indicate where a particular device type is likely to be displaced from the market by a more attractive alternative e.g. fast thyristors by the GTO thyristors [44, 45, 46].

Some important power electronic devices are given as follows:

(1) Diodes

Though not controllable, diodes are used in snubber circuits and as free-wheel elements in converters employing bimodal devices such as the GTO. Converter grade diodes (which are optimised for low on-state volt drop) are too slow for these applications. Fast diodes are available with maximum repetitive reverse blocking voltages up to about 6 kV, diameters up to 75 mm.

(2) Thyristors

Having a pnpn structure instead of the simple pn or pin structure of diodes, the thyristor is able to block forward voltage. It is triggered into a (latched) conducting state by the application of a gate pulse and thereafter conducts until the current is quenched by circuit commutation, when the thyristor undergoes negative recovery in a similar fashion to the diode. Power thyristors are generally available as double side cooled capsules with silicon diameters presently up to 100 mm. Forward and reverse peak voltage ratings of up to about 8 kV are available.

(3) Light Triggered Thyristors (LTT)

Direct optical triggering of thyristors connected in series strings, as in high voltage converter valves, is highly desirable since it removes the need for local gate electronic units at each thyristor level, in addition to providing interface immunity in a noise electrical environment. However, the gate units currently associated with electrically triggered thyristors also protect the thyristor from damage which might result from ungated self-turn-on from causes such as exceed dv/dt, overvoltage, and insufficient forward recovery. Light triggered thyristors are already available at the highest ratings, but for them to be successfully applied, self-protection functions must be integrated onto the thyristor wafer.

(4) Gate Turn-Off Thyristors (GTO)

The GTO has a basic thyristor structure but contains a large number, over 3000 for the largest sizes, of cathode emitter islands, each completely surrounded by gate structure. Extraction of sufficient gate current, more than 20% of the anode current level, quenches the emitter action and turn off the GTO. Forward gate current flow in the region 5 - 10 A is needed to maintain conduction should the anode current fall below the relatively high holding current level of about 100 A.

The GTO has two types. The symmetric reverse blocking type suffers from slow switching speeds and high switching losses. The anode shorted type has limited reverse blocking capability and requires the protection of anti-parallel diode connected across it, but has tolerable switching loss and adequately fast switching. Employing fast rising high current gate drive, the turn-on time is about 5 μs and the turn-off time is about 20 μs at full 4 kA rating. To prevent damage occurring at switching, any conduction interval between successive periods of conduction must exceed a minimum off time. For the largest devices these times are about 100 μs each.

To achieve satisfactory turn-off, a low inductance diode-coupled snubber capacitor must be employed, both to limit spike voltage energy dissipation and to prevent dv/dt re-triggering following turn-off. With modern fine-finger geometry GTOs, the size of snubber capacitor required has reduced, It is presently about 1 μF per 1 kA of turn-off current. A series inductor is used to limit di/dt at turn-on.

(5) Bipolar Junction Transistor (BJT)

Having a three-layer npn structure, the BJT requires substantial continuous base drive to maintain conduction. Pressure contact capsules are available using 40 mm diameter silicon, having 1 kV peak voltage withstand and 400 A continuous current rating. However, the BJT is unlikely to develop beyond its present status owing to its limited voltage rating and to the greater potential of GTOs and IGBTs.

(6) Field Controlled Thyristor (FCT)

The FCT, otherwise called the Static Induction Thyristor (SITh), contains a gird of closely spaced gates which separate the basic diode structure into a very large number of cells. There are two types depending on the gap between the gates: approximately 5 μm for the normally-on type, and approximately 1 μm for normally-off. Negative gate current extracted via the grid pinches off the anode to cathode current flow, so causing and speeding up turn-off. Forward gate current causes and enhances turn-on. Voltage ratings of 2.5 kV and controllable currents of over 1 kA has been reported. Relatively high manufacturing costs are likely to limit further development of this device.

(7) MOS Power Devices

Power semiconductor devices based on Metal Oxide Semiconductor (MOS) technology have the common feature of being composed of very small cells, typically 10 -30 μm in width. There are three main device types: the power MOS Field Effect Transistor (MOSFET), the Insulated Gate Bipolar Transistor (IGBT) and the MOS-Controlled Thyristor (MCT).

(8) MOSFET

Unlike the directly contacting pn junction gate used for the control of devices described earlier, the MOS gate is capacitively coupled and functions by inducing a charged layer within a semiconductor. The fine structure of MOS devices means that there is a high probability of process defects which could result in unacceptably low yield if prepared as single large diameter wafers. Thus present day devices are generally in the form of isolated base plastic modules. The highest rated MOSFET module has peak off-state voltage 1 kV and average current ratings of about 400 A. Its switching speeds are $T_{\text{turn-on}}$=100 ns, $T_{\text{turn-off}}$=500 ns. These high speeds dictate that undamped stray circuit inductance must be minimised; voltage limiting devices and small snubber circuits may be beneficial.

(9) IGBT

The IGBT has a similar gate structure to the MOSFET but contains a highly doped layer (p+) next to the collector for the purpose of emitting holes to produce conductivity modulation of the lightly doped n-base region. IGBT modules with voltage ratings as high as 3.3 kV peak are expected to become available soon.

The IGBT is becoming increasingly popular owing to its ease of mounting, its ease of driving common to all MOS devices and the fact that it has inherent short circuit capability, albeit of short (10μs) duration. Because it has high switching speed and low switching loss, and can also be switched snubberless in a suitably low inductance circuit, the IGBT can be operated at high PWM frequency, typically several kHz for large units. The IGBT has a number of important limitations. Until recently, available voltage ratings have limited its applications. Because there is a significant thermal resistance between base and heatsink, sometimes as high as 30 % of the total from junction to heatsink.

(10) MCT

Conducting in the latched state without the aid of gate bias, it has a low on-state drop and is capable of withstanding high surge currents. MOS control is on the anode side of the device. Because it has poor Reverse Bias Safe Operating Area, the MCT has not been developed to the highest ratings and has failed to find general application, except where soft switching at low power levels is involved, e.g. in resonant circuits.

2.2.2 Factors Influencing Power Electronic Device Selection

In the applications of power electronic devices, many factors influence the selection of them but all can be reduced, ultimately, to a compromise between performance and overall cost. Power system applications tend to be characterised by a requirement for very long design life (typically 30 years) and very onerous reliability and availability requirements, leading to a strong preference for simple designs using well proven technology [47]. The pressure to utilise devices with the highest possible current and voltage ratings may be considerable; however, when overall costs are evaluated, the apparent advantage of requiring fewer devices can often be outweighed by disproportionately higher device (and auxiliary component) costs, poorer dynamic performance or higher losses.

Some examples of applications of these devices in the HVDC and FACTS are described as follows:

(1) HVDC

For HVDC valves, the thyristor has many advantages: it is available in high voltage and current ratings, has low losses and failure and can readily be connected in series strings. For some HVDC applications, forced commutation using GTOs may find applications, for example when feeding a dead load. However, the higher losses (in comparison with thyristors), onerous gate drive requirements and relative complexity of connecting devices in series are likely to remain severe limitations.

(2) FACTS

For FACTS equipment requiring fully controllable devices, the GTO thyristor is the present choice, despite its poor utilisation of silicon (making it comparatively lossy) and its challenging gate drive and snubber circuit demands. It is available at high current and voltage ratings and, subject to selection for matched characteristics and attention to equipment design, it can be used in series strings (although this is less straightforward than for conventional thyristors).

The high switching losses associated with GTOs limit their use to relatively lower frequencies, typically up to about 1 kHz. Therefore, whilst they find applications in ac active filters for HVDC schemes, this tends to be only for the lowest harmonics. At higher harmonics, where power levels also tend to be lower, they tend to be unsuitable.

Although not yet available in ratings comparable with GTOs and thyristors, the IGBT has much lower switching losses that the GTO and is therefore much better suited to applications involving switching frequencies in excess of about 1 kHz. IGBTs have minimal gate drive and snubbing requirements; moreover, voltage and current ratings of IGBTs have recently been increasing rapidly, driven by pressure from traction markets. The most promising immediate application for IGBTs lies in active filtering. Here, switching frequencies are high, voltage and power levels are comparatively modest and series connection of devices is unnecessary (since the required ratings can be achieved with traditional circuit topologies).

For superconducting magnet energy storage (SMES) applications, the natural choice of technology for the interfacing power electronics is the current source converter, rather than the more common voltage source inverter. The use of a current source converter requires a device with reverse voltage blocking capability in addition to full controllability. Such requirements are fulfilled by reverse blocking GTOs, which are technically feasible but have inferior switching characteristics when compared with usual anode-shorted GTO.

2.3 Fundamental Theory of FACTS in Operations of Transmission Systems

As is well known, the power flow in an ac transmission system is a function of the transmission line impedance, the magnitude of the sending and receiving end voltage, and the phase angle between these voltages. The objective of FACTS is to control, concurrently or selectively, all of these parameters [48, 49, 50]. In order to put FACTS concept into perspective, the basic power flow relationships of ac transmission systems are reviewed. Corresponding to these power flow concepts, application theories of some FACTS devices are introduced.

The review of basic relationships for power transmission is, for simplicity, limited to the simple two machine models shown in Figure 2-2. Figure 2-2 (a) shows the sending-end generator with voltage phasor V_S, the receiving-end generator with voltage phasor V_R, the transmission line impedance X (assumed inductive) in two sections (X/2), and a generalised power flow controller operated (for convenience) at the middle of the line. The power flow controller consists of two controllable elements, a voltage source (V_{pq}), inserted in series with the line, and a current source (I_q), connected in shunt with the line at the midpoint. Both the magnitude and the angle of voltage V_{pq} are freely variable, whereas only the magnitude of current I_q is variable; its phase angle is fixed at 90 degrees with respect to mid-point voltage V_M (which is assumed to be the reference phasor with zero phase angle). Note that the above definitions for V_{pq} and I_q mean that former can exchange reactive and active power whereas the latter only reactive power.

The four classical cases of power transmission, (1) without line compensation, (20 with series capacitive compensation associated with SVC and STATCON, (3) with shunt compensation associated with TCSC, and (4) with phase angle control associated with TCPAR, phase shifter and quadrature booster, can be obtained by appropriately specifying V_{pq} and I_q in the generalised power flow controller shown in Figure 2-2 (a).

For case (1), assume the both V_{pq} and I_q are zero (power flow controller is off). Then the power transmitted between the sending and the receiving end generators can be expressed by the well known formula (assuming that V_R=Vs=V):

$$P_{(1)} = \frac{V^2}{X}\sin\delta \qquad (2\text{-}1)$$

where δ is the angle between the sending and receiving end voltage phasors. Power $P_{(1)}$ is shown plotted against angle δ in Figure 2-2 (b), curve (1).

For case (2), assume that I_q =0 and V_{pq}=-jkXI, that is, the voltage inserted in series with the line lags the line current by 90 degrees with an amplitude that is proportional to the magnitude of the line current and that of the line impedance. In other words, the voltage source acts as the fundamental frequency precisely as a series compensating capacitor. The degree of series compensation is defined by coefficient k ($0\leq k \leq 1$). With this, the P versus δ relationship becomes:

$$P_{(2)} = \frac{V^2}{X(1-k)}\sin\delta \tag{2-2}$$

Power $P_{(2)}$ is shown plotted against angle δ by curve (2).

For case (3), assume that $V_{pq}=0$ and $I_q=-j(4V/X)[1-\cos(\delta/2)]$, that is, the current souce I_q draws just enough capacitive current to make the magnitude of the mid-point voltage equal to V. In other words, the reactive current source acts like an ideal shunt compensator which segments the transmission line into two independent parts, each with an impedance of X/2, by generating the reactive power necessary to keep the mid-point voltage constant, independently of angle δ. For this case of ideal mid-point compensation, the P versus δ relationship can be written as:

$$P_{(3)} = 2\frac{V^2}{X}\sin\frac{\delta}{2} \tag{2-3}$$

Power $P_{(3)}$ is shown plotted against angle δ by curve (3).

For case (4), assume that $I_q=0$ and $V_{pq}=\pm jV_M\tan\alpha$, that is, a voltage ($V_{pq}$) with amplitude $\pm jV_M\tan\alpha$ is added in quadrature to the mid-point voltage (V_M) to produce the desired α phase shift (leading or lagging). The basic idea behind the phase shifter is to keep the transmitted power at a desired level independently of angle δ in a predetermined operating range. Thus, for example, the power can be kept at its peak value after angle δ exceeds π/2 (the peak power angle) by controlling the amplitude of quadrature voltage V_{pq} so that the effective phase angle (δ-α) between the sending and receiving-end voltages stays at π/2. In this way, the actual transmitted power may be increased significantly, even though the phase shifter per se does not increase the steady state power transmission limit. (Of course, it does increase the transient and dynamic stability of the system.)

Considering (δ-α) as the effective phase angle between the sending and receiving end voltages, the transmitted power P can be expressed as follows:

$$P_{(4)} = \frac{V^2}{X}\sin(\delta - \alpha) \qquad (2\text{-}4)$$

Power $P_{(4)}$ is shown plotted against angle δ by curve (4).

The expressions given by equations (2-2) through (2-4) define the relationship between the transmitted power and the transmission angle with series and shunt compensation, and phase shifting, which are theory foundations of SVC, STATCON, TCSC, TCPAR, phase shifter and quadrature booster. It should be noted that these expressions are for steady state conditions, that is, they define the transmitted power for given end voltages, line impedance, and angle. The idea behind these FACTS concepts is to control these parameters in real time and thereby vary (increase or decrease) almost instantaneously the transmitted power according to prevailing system conditions [51, 52]. The ability to control power rapidly, within appropriately defined boundaries, can increase the transient (first swing) stability, as well as the damping of the system. Increased transient stability and damping allow a corresponding increase in the permissible steady state power transmission and thus a higher utilisation of the system. Table 2-1 lists these FACTS controllers as well as other several important FACTS devices along with their attributes.

2.4 Typical FACTS Devices

After power electronics devices and some FACTS operation concepts in transmission systems have been reviewed, it can be concluded that FACTS technology can be presently utilised in transmission systems on the basis of these high power electronics devices. Some FACTS devices such as SVC, STATCON and TCSC have been implemented in practical systems and more experiences of FACTS operations have been obtained. It can be predicated that other power electronics based FACTS controllers will be available in the market in near future. The following sections [53] will illustrate those power electronics based FACTS devices which have been used or will be soon installed in practical systems, not including both those mechanical control devices and those only in the period of conceptual design of power electronics based FACTS devices such as phase shifter, quadrature booster and SSSC (Static Synchronous Series Compensator).

2.4.1 SVC

Several FACTS controllers are already being evaluated or used, while others have been considered in concepts but have yet to be invented. What might be called the first generation of FACTS controllers includes two thyristor-based devices that have found limited use on utility systems for several years. The first FACTS device, a Static Var Compensator (SVC), has been used since the mid-1970's and addresses the problem of maintaining steady state and dynamic voltages within acceptable limits, with a moderate capability to control stability, but with no capability to control power flow. The SVC uses thyristor control to rapidly add or remove shunt connected reactors and/or capacitors, often in co-ordination with mechanically controlled reactors/capacitors. It was demonstrated by GE on the Tri-State G&T System in 1977. Another AVC with voltage and stability control, developed by Westinghouse, began operation in 1978 on the Minnesota Power and Light System (Figure 2-3). It is interesting to note that since the launching of the FACTS strategy, the market for SVCs has substantially increased.

2.4.2 NGH-SSR Damper

The second existing FACTS controller is NGH-SSR Damper, invented by Dr. N.G.Hingorani, to counter subsynchronous resonance (SSR). Such SSR instabilities can arise as an undesirable side effect of adding 20 to 30% mechanically controlled series capacitors to a transmission line, to lower its impedance and increase power flow and stability limits. During the early 1970's, after the shaft of a turbine generator belonging to Southern California Edison was damaged by SSR, series compensation on a major 500 kV transmission corridor had to be reduced, resulting in lower power transfer capability. Since then, various solutions of sensing, emergency switching, blocking of SSR, etc., have been adopted. In this SSR Damper (Figure 2-4), the thyristor have a modest current rating (15% of load current), for continuously bypassing the capacitor for only the last ten degrees or so. This damper also forms the technological basis for the fully rated thyristor controlled series capacitor described below.

2.4.3 TCSC

For effective power and stability control, the ability to control impedance or phase angle is obviously the most important need. Since the series impedance of a line is virtually all inductive, with only 5 to 10% resistive impedance, it is convenient to add a thyristor controlled series capacitor to be able to continuously vary the impedance to values up to the line's natural impedance and to add a thyristor controlled series reactor to continuously vary the impedance to values higher than the line's natural impedance. Once installed for controlling steady state impedance of the power system, either of these systems can rapidly respond to modulation signals to damp dominant oscillation frequencies that would otherwise lead to instabilities and/or unacceptable dynamic conditions during and after disturbances.

The first new FACTS controller demonstrated on a utility transmission system, is the thyristor controlled series capacitor (TCSC). In 1991, American Electric Power began testing a prototype thyristor controlled switch on one phase of the series capacitor bank at its Kanawha River 345 kV Substation in West Virginia. In October, 1992, the Western Area Power Administration (WAPA) dedicated the first three-phase TCSC installation. It was built by Siemens and installed at the WAPA Kayenta Substation in Arizona in a 200 mile, 230 kV, 300 megawatt transmission line. This installation represents a pioneering step because one of the 15-ohm banks controlled by thyristors can be controlled continuously and rapidly from 15 to 60 ohms through the controlled firing angle of the thyristor valves, as in the SSR damper, but over a wider range from 145 degrees to 180 degrees. The installation allows the transmission line capacity to be increased from 300 megawatts to 400 megawatts.

TCSC installation on a 500 kV line featuring the full range of controls and operating requirements was demonstrated by GE at the Slatt Substation of Bonneville Power Administration (Figure 2-5). The TCSC includes features of impedance control, power control, current control remotely through a Supervisory Control and Data Acquisition

(SCADA) system, SSR mitigation, power swing damping, transient stability control, various local protection features, overload management and module order logic.

2.4.4 STATCON

As mentioned earlier, the SVC using thyristor switches is already a firmly estabilished equipment for voltage control. However, another concept called the Static Condenser, or STATCON (Figure 2-6), will substantially replace the SVC because of its superior performance. Basically, the STATCON is a three phase inverter that is driven from the voltage across a dc storage capacitor and it generates a set of three output voltages, which are in phase with the ac system voltages. When the output voltages are higher or lower than the ac system voltages, the current flow is caused to lead or lag, respectively, and the difference in the voltage amplitude determines the magnitude of current flow. In this manner, reactive power and its polarity can be controlled by controlling the voltage.

The superior performance results from the fact that the maximum reactive power that can be delivered from the STATCON equals the voltage times the current, whereas in the case of the SVC, it is the voltage squared divided by the impedance. Thus, if the voltage is depressed, the STATCON can still deliver high levels of reactive power by using its overcurrent capability; whereas with the SVC, the reactive power drops drastically as a function of the square of the voltage -- just when it is needed. In addition, a STATCON provided with a large capacitor or large storage device, such as battery, can continue to deliver some energy for a short time, just as a synchronous condenser does because of the stored energy in its rotating mass. Thus, depending on the application, the rating of the STATCON required will be much smaller than the comparable SVC.

A STATCON developed by EPRI with Westinghouse was demonstrated in 1988 at Orange and Rockland Utilities, as an experimental 1 Mvar STATCON. Now, under EPRI sponsorship with Westinghouse, a 100 Mvar STATCON is ready for demonstration at Sullivan Substation.

2.4.5 UPFC

An initial task of the UPFC Project [54], so-called 'Inez Project' will be to identify the potential applications associated with the UPFC installation. American Electric Power (AEP), The Electric Power Research Institute (EPRI) and Westinghouse are developing the new breed of power delivery technology and has committed tens of millions of dollars to reap the benefits from what they think of as the definitive FACTS device, the UPFC. The highlights of the Inez projects are: a new high capacity 138 kV line, a line flow control device to fully utilise the new 138 kV line, a series reactor on a thermally limited line, a dynamic reactive source for voltage control, and a new 345 kV to 138 kV transformer. The two control devices together function as a UPFC.

The diagram of UPFC arrangement for this application is shown in Figure 2-7. The benefits produced by the UPFC are illustrated by a typical case in Figure 2-8. The UPFC increases the line flow by about 125 MW, while simultaneously regulating the area voltage within an excellent 1 percent. The overall benefits can be summarised up as follows:

- Thermal overload and low voltages are eliminated.
- Adequate power supply will be available for several years of growth.
- Active power system losses will be reduced by more than 24 MW for net capital equivalent savings of $22 million.
- An 85,000 ton annual CO_2 reduction.

The project has commenced in 1996 and all facilities associated with this project in the Inez and Tri-State areas will be service by the summer of 1999. It is the first UPFC application in the world and it is believed that its success would extend the market reach of FACTS devices.

2.5 Advantages and Benefits of FACTS Technology

FACTS is defined as 'a technology that embraces applications of power electronics applied to transmission system except HVDC ' by Dr. N.G.Hingorani. Although there are many diverse opinions on FACTS definitions, it does not matter as long as it brings potential advantages and benefits to transmission systems:

(1) Cost

Due to the high capital cost of transmission plan, cost considerations frequently outweigh all other considerations. Compared to alternative methods of solving transmission loading problems FACTS technology is often the most economic alternative.

(2) Convenience

All FACTS devices can be retrofitted to existing ac transmission plant with varying degrees of ease. Compared to HVDC or six-phase transmission schemes, solutions can be provided without wide scale system disruption and within a reasonable time scale.

(3) Environmental impacts

In order to provide new transmission routes to supple an ever increasing worldwide demand for electrical power, it is necessary to acquire wayleave - the right to convey electrical energy over a given route. It is common for environmental opposition to frustrate attempts to establish new transmission routes. FACTS technology, however, allows greater throughout over existing routes, thus meeting consumer demand without construction of new transmission lines. However, the environmental impact of the FACTS device itself may be considerable. In particular, series compensation units can be visually obtrusive with large items of transmission equipment placed on top of high-voltage insulated platforms.

2.6 Summary

The chapter first reviewed the attributes of the various modern power electronic devices and assessed their potential applications in electrical power transmission networks. Then, the fundamental theory of transmission systems associated with FACTS applications was introduced. Some representative applications of FACTS devices in practical systems were presented. Finally, the advantages and benefits of power electronics based FACTS technology were summarised. This chapter provides a background for further discussion of the UPFC in Chapter 3.

Table 2-1 Some key FACTS controllers and their attributes

FACTS Controllers	Attributes
NGH-SSR Damper	Damping of oscillations, series impedance control, transient stability
Static VAR Compensator (SVC)	Voltage control, VAR compensation, damping of oscillations
Thyristor Controlled Series Capacitor (TCSC)	Power control, series impedance control, damping of oscillations, transient stability
Static Synchronous Series Compensator (SSSC)	Power control, series impedance control, damping of oscillations, transient stability
Thyristor Controlled Series Reactor (TCSR)	Power control, series impedance control, damping of oscillations, transient stability
Static Condenser (STATON)	Voltage control, VAR compensation, damping of oscillations, transient stability
Phase Shifter, Quadrature Booster	Power control, phase angle control, damping of oscillations, transient stability
Thyristor Controlled Phase Angle Regulator (TCPAR)	Power control, phase angle control, damping of oscillations, transient stability
Unified Power Flow Controller (UPFC)	Power control, VAR compensation, voltage control, phase angle control, damping of oscillations, transient stability
Thyristor Controlled Dynamic Brake	Damping of oscillations, transient stability
Thyristor Controlled Dynamic Voltage Limiter	Limits dynamic overvoltages

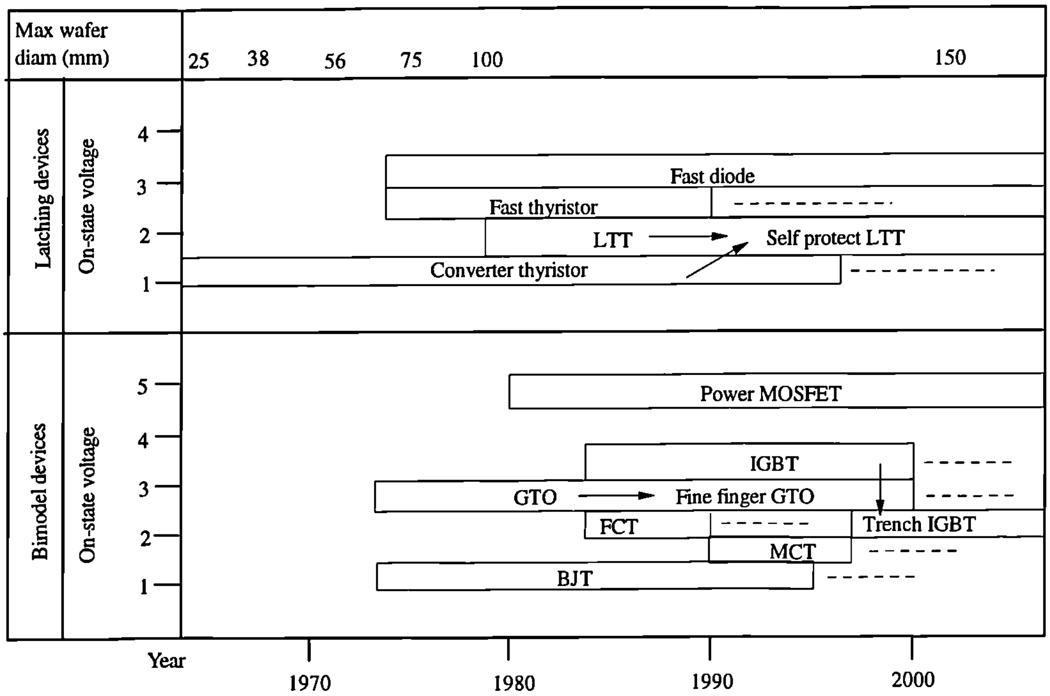


Figure 2-1 Silicon power device evolution

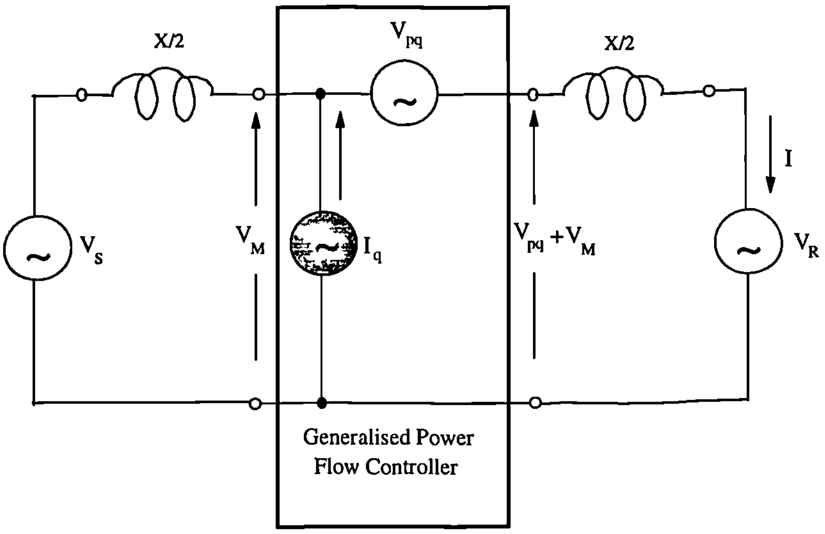
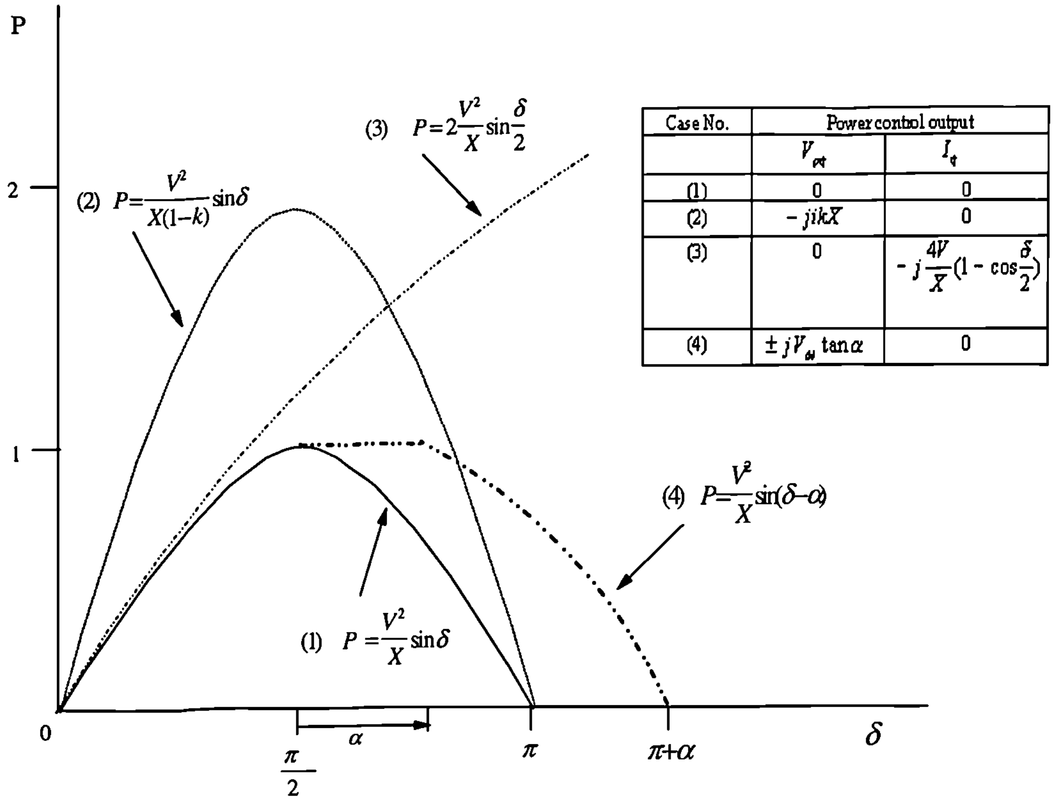


Figure 2-2 (a) Simple two-machine power system with a generalised power flow controller



Case No.	Power contbol output	
	V_{pq}	I_q
(1)	0	0
(2)	$-jikX$	0
(3)	0	$-j\frac{4V}{X}(1-\cos\frac{\delta}{2})$
(4)	$\pm jV_{\omega}\tan\alpha$	0

Figure 2-2 (b) Four power transmission characteristics with a generalised power flow controller

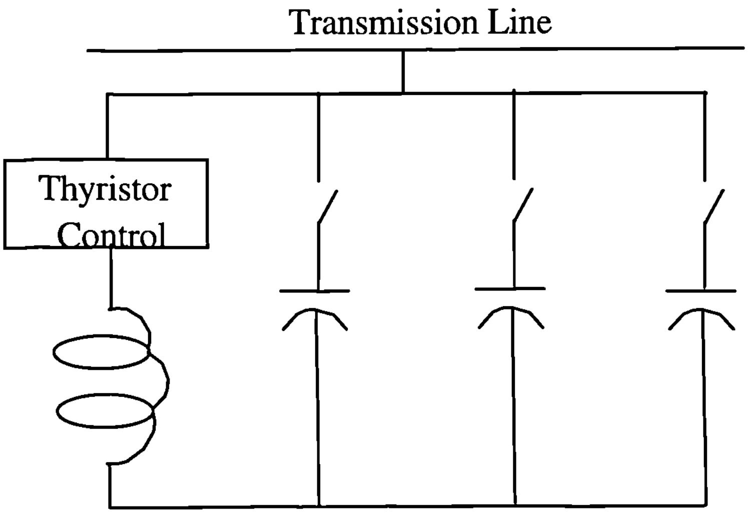


Figure 2-3 Static Var Compensator on Minnesota Power & Light System

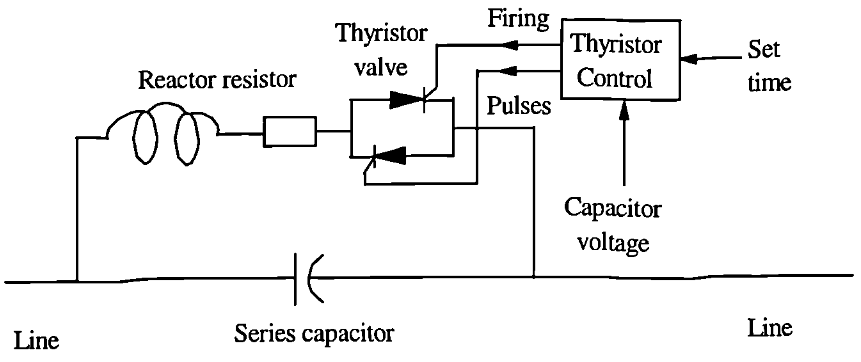


Figure 2-4 NGH-SSR Damping device for series capacitor at SCE Lugo Substation

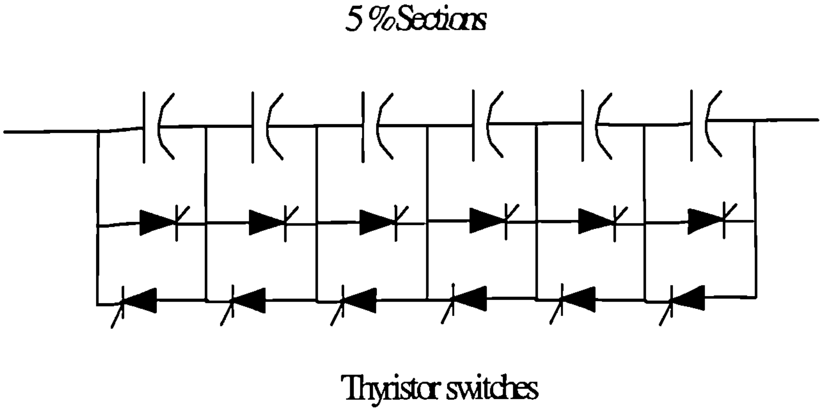


Figure 2-5 TCSC at BPA Slatt Substation

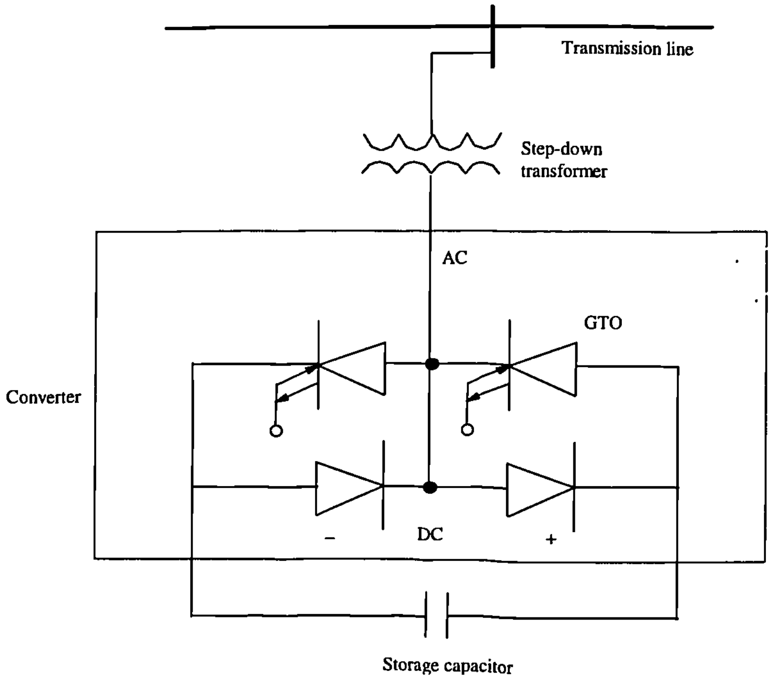


Figure 2-6 Static Condenser (STATCON)

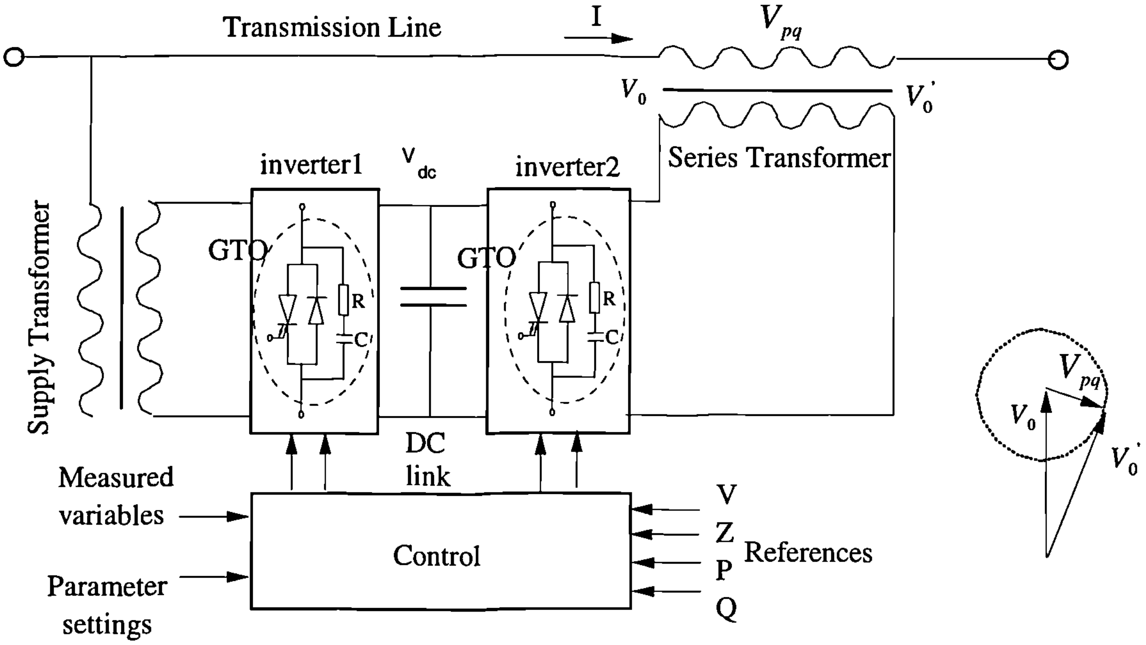


Figure 2-7 Implementation of the UPFC using two voltage-sourced inverters with a direct voltage link

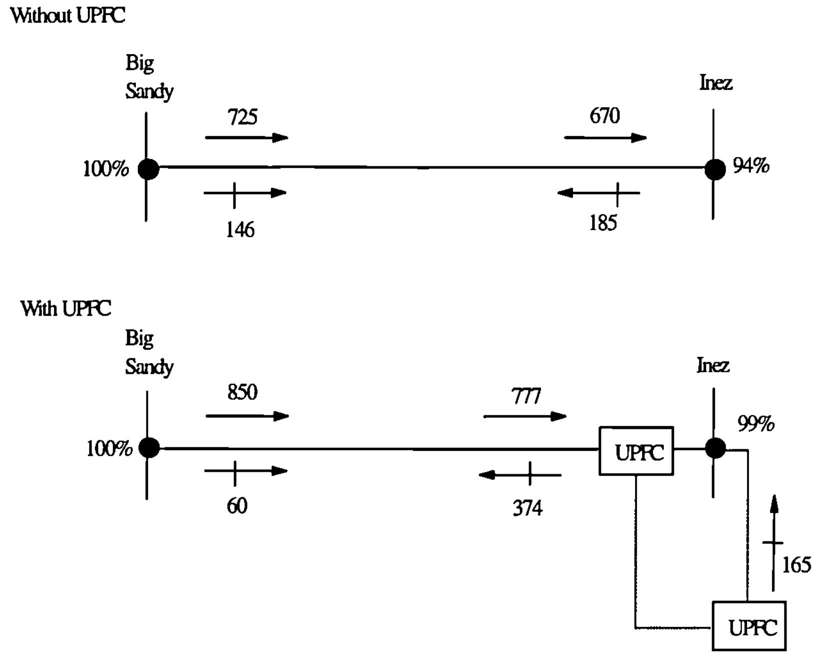


Figure 2-8 System performance

Chapter 3

UPFC: PRINCIPLE, MODELLING AND CONTROL

3.1 Introduction

Although the UPFC has received much attention since it was proposed and will be initiated in a practical system as described in Chapter 2, few literature systematically addressed the modelling, algorithms and control strategies for UPFC from a system point of view. Many of the papers treated the UPFC from the experiences gained from other FACTS devices without considering its unique characteristics. Secondly, most work done so far is based on the conceptual model of the UPFC.

This chapter will deal with the operation theory of UPFC. The general UPFC structure will then be developed. Finally, the details about every aspect of its modelling, algorithms and control strategies will be reviewed.

3.2 Principles of UPFC

3.2.1 UPFC Operation Theory

Consider again the generalised power flow controller shown in Figure 2-2 (a) of Chapter 2 [12]. Assume that the voltage source V_{pq} in series with the line can be controlled without restrictions. That is, the phase angle of phasor V_{pq} can be chosen independently of the line current between 0 and 2π, and its magnitude is variable between zero and a defined maximum value, V_{pqmax}. This implies that voltage source V_{pq} must be able to generate and absorb both active and reactive power with a variable magnitude ($0 \le I_q \le I_{qmax}$) that is independent of the terminal voltage.

To investigate the basic characteristics of the generalised power flow controller, assume that its input terminal is connected to the generator (V_s) via a transmission line-segment (X_L) and the magnitude $V_o^{'}$ of voltage phasor $V_o^{'}$ at this terminal is kept constant by the reactive current source I_q. Voltage $V_o^{'}$ and impedance X_L may be different from V_M and X/2, that is, in the present model, the power flow controller is not necessary located at the mid-point of the line. The voltage phasor V_0 at the output terminal of the power flow controller is assumed to be again the reference phasor and it is given by $V_0 = V_0^{'} - V_{pq}$. A constant current I, determined by the receiving-end part of the power system, is assumed to be drawn from the output terminal of the power flow controller [30].

Power flow control is achieved by adding voltage source V_{pq} is stipulated to have no angular restrictions, and its magnitude is variable between 0 and V_{pqmax}, its end-point can be anywhere inside a circle with a radius of V_{pqmax}, whose center is at the end of reference phasor V_0, as shown in Figure 3-1 (a). This means that by the appropriate definition (control) of phasor V_{pq}, the generalised power flow controller can be used to accomplish the following objectives:

(1) Dedicated terminal voltage regulation or control, which is obtained simply by keeping the angle of V_{pq} zero (i.e., $V_{pq} = \pm\Delta V_0$), and thus changing only the magnitude of $V_o^{'}$ with respect to that of V_0 (or vice versa), as illustrated in Figure 3-1 (b).

(2) Combined series line compensation and terminal voltage control, which is obtained by defining V_{pq} as a sum of voltage phasors V_c and ΔV_0, that is, $V_{pq} = V_c + \Delta V_0$, where phasor V_c is perpendicular to line current I (i.e., $V_c = kI\exp(\pm j\pi/2)$ and ΔV_0 is in phase with the terminal voltage phasor V_0. Voltage V_c decreases or increases the effective voltage drop across the line segment impedance X_L according to whether V_c lags or leads I, as illustrated in Figure 3-1 (c).

(3) Combined phase angle regulation and terminal control, which is obtained by defining V_{pq} as a sum of voltage phasors V_α and ΔV_0, that is, $V_{pq} = V_\alpha + \Delta V_0$, where $V_\alpha = 2V_0 \sin\frac{\alpha}{2}\exp\left[\pm j(\frac{\pi}{2} - \frac{\alpha}{2})\right]$, and ΔV_0 is again in phase with the terminal voltage V_0.

The selected definition for phasor V_α ensures that the resultant terminal voltage phasor at the end of line segment, $V_0' = V_0 + V_\alpha + \Delta V_0$, has the same magnitude as $V_0 + \Delta V_0$, but its phase angle is different from that of V_0 by α, as illustrated in Figure 3-1 (d). In practical terms this means that phase-shifting is achieved without any unintentional magnitude change in the controlled terminal voltage.

(4) Combined terminal voltage regulation and series line compensation and phase angle regulation, which can be achieved by synthesising the injected voltage phasor V_{pq} from the three individually controlled phasors, that is $V_{pq} = V_c + V_\alpha + \Delta V_0$, as illustrated in Figure 3-2.

The unified power flow control approach can be broaden the basic power transmission concepts. This approach allows not only the combined application of phase angle control with controllable series and shunt compensations, but also the real time transition from one selected compensation mode into another one to handle particular system contingencies more effectively comparing with the theories of other FACTS applications described in Chapter 2. (For example, series reactive compensation could be replaced by phase-angle control or vice versa.) This may become especially important in complex transmission systems where control compatibility and co-ordination of various FACTS devices must be maintained in face of equipment failures and system changes. The approach would also provide considerable operating flexibility by its inherent adaptability to power system expansions and changes without any hardware alterations.

3.2.2 Modelling and Control Prototype of UPFC

There are a number of feasible solid-state implementations for the UPFC. The implementation considered feasible and economical with presently available power semiconductors is akin to those proposed for the static condenser, advanced controllable series compensator, and phase shifter. It employs voltage-sourced inverters (i.e., inverters fed from a dc voltage source), composed of gate-turn off (GTO) thyristor valves, in appropriate harmonic neutralized configurations which ensure almost distortion-free output, economic manufacturing, and inherent redundancy for multilevel partial availability.

The proposed implementation of the UPFC, using two voltage sourced inverters operated from a common dc link capacitor, is shown schematically in Figure 2-7 of Chapter 2. This arrangement is actually a practical realisation of an ac to dc power converter with independently controllable input and output parameters.

Inverter 2 is used to generate voltage $V_{pq}(t) = V_{pq}\sin(\omega\,t - \phi_{pq})$ at the fundamental frequency (ω) with variable amplitude ($0 \le V_{pq} \le V_{pqmax}$) and phase angle ($0 \le \phi_{pq} \le 2\pi$), which is added to the ac system terminal voltage $V_0(t)$ by the series connected coupling (or insertion) transformer. With these stipulations, the inverter output voltage injected in series with the line can be used for direct voltage control, series compensation, and phase shift, as discussed in the previous section.

The inverter output voltage injected in series with the line acts essentially as an ac voltage source. The current flowing through the injected voltage source is the transmission line current that is a function of the transmitted electric power and impedance of the transmission line. The VA rating of the injected voltage source (i.e., that of Inverter 2) is determined by the product of the maximum injected voltage source and the maximum line current at which power flow control is still provided. This total VA is made up of two components: one is the maximum active power determined by the maximum line current and the component of the maximum injected voltage that is in phase with this current, and the other one is the maximum reactive power determined by the maximum line current and the component of the maximum injected voltage that is in quadrature with this current. As known, the voltage sourced inverter used in the implementation, can internally generate or absorb at its ac terminal all the reactive power demanded by the voltage/impedance/phase angle control applied and only the active power demand has to be supplied at its dc input terminal.

Inverter 1 (connected in shunt with the ac power system via a coupling transformer) is used primarily to provide the active power demand of Inverter 2 at the common dc link terminal from the ac power system. Since Inverter 1 can also generate or absorb reactive power at its terminal, independently of the active power it transfers to (or from) the dc terminal, it follows that, with proper controls, it can also fulfil the function of the independent static condenser providing reactive power compensation for the transmission line and thus executing an indirect voltage regulation at the input terminal of the UPFC.

The internal control of the solid-state power flow controller illustrated in Figure 2-7 is structured so as to accept externally derived reference signals, in an order of selected priority, for the desired reactive shunt compensation, series compensation, transmission angle, and output voltage. These reference signals are used in closed control-loops to force the inverters to produce the ac voltages (which corresponds to the appropriate combination of the reference signals) at the input (shunt-connected) and output (series-connected) terminals of the power flow controller, and thereby establish transmission parameters desired. While these signals feeding to internal control of UPFC are generated from local or global controllers under other operation states. Thus, for every UPFC controller and global system controller, the control structure is hierarchical. Figure 3-3 shows that modelling and control of UPFC are associated with three main operation states and three levels of control structure. For different states and different controllers, UPFC has various forms of model expressions and different control objectives.

3.3 Electromagnetic Transient Modelling and Control of UPFC

3.3.1 Modelling

The modelling of UPFC under electromagnetic transient state is quite different from other states' models which are mathematical with reasonable assumptions and simplifications. However, UPFC model for electromagnet transient state often requires the detailed circuit construction of the practical UPFC implementation. Thus, in order to investigate the UPFC's electromagnetic transient model and the associated problems, one needs to understand what kind of arrangements can be adopted in the practical implementation of UPFC.

The concept of the UPFC was proposed based on the development of voltage-source inverter structure, in which GTO devices are employed. A prototype of three phase six-pulse bridge voltage source inverter, which is the most basic forms of half part of realising UPFC circuit, is shown in Figure 3-4. The principle of operation is that the GTO inverter converts a dc voltage into a three-phase ac voltage which is synchronised and connected to the ac system through a small tie reactance, usually the leakage reactance of a transformer. When the inverter output voltage is higher than the ac system voltage, leading reactive current is drawn from the system (vars are generated) . When the inverter output voltage is lower than the ac system voltage, lagging reactive current is drawn from the system (vars are absorbed). When the inverter output voltage is equal to the ac system voltage, the reactive power is zero [55, 56]. The design is compact with the variation of reactive power achieved through control action of the bridge and offers fast continuous variation of reactive output power from capacitive to inductive, and a more effective reactive power generation during undervoltages. The UPFC adopts such features for its operation.

However, when high powers are required, some VSI configurations based on such the three-phase VSI can be used, which are pictured in Figure 3-5, 3-6 and 3-7. Although these configurations have their own characteristics [57, 58, 59, 60, 61], their fundamental operations are similar to the aforementioned.

It seems that these circuits constructed for UPFC are not complicated in appearance. However, in fact, there are many problems associated with the internal control of such circuits and highly non-linearity arising from switch actions, which will be explained further in next two sections.

3.3.2 Internal Control of UPFC

The key problem associated with the simulation of electromagnetic transient state UPFC model is its internal control, that means what control methods of UPFC should be adopted. This control not only depends on the structure, arrangement and power electronics devices adopted by UPFC, it is also determined by functions provided by UPFC. As UPFC consists of two VSI types of circuits and they have different objectives, both VSI circuits can then adopt different control methods or the same modulation schemes. The control of the VSI circuit has been widely used in electrical engineering applications [62, 63, 64, 65, 66, 67, 68], especially in low-voltage small power rating aspects. The control of the VSI circuit described in the previous section can be divided into the following two general categories:

(1) Pulse-width-modulated inverters [69, 70]: In these inverters, the input dc voltage is essentially constant in magnitude, such as in the circuit of Figure 3-4, where a diode rectifier is used to rectify the line voltage. Therefore, the inverter must control the magnitude and the frequency of the ac output voltage. This is achieved by PWM of the inverter switches and hence such inverters are called PWM inverters. There are various schemes to pulse-width modulate the inverter switches in order to shape the output ac voltages to be as close to a sine wave as possible. Out of these various PWM schemes, a scheme called the sinusoidal PWM (SPWM) will be used in the thesis.

(2) Square-wave inverters: In these inverters, the input dc voltage is controlled in order to control the magnitude of the output of the output ac voltage, and therefore the inverter has to control only the frequency of the output voltage. The output ac voltage has a waveform similar to a square wave, and hence these inverters are called square-wave inverters.

The relationship between the control input and the full-bridge inverter output magnitude can be summarised as shown in Figure 3-8 (a), assuming a sinusoidal PWM in the linear range of $m_a \leq 1.0$. For a square-wave switching, the inverter does not control the magnitude of the inverter output, and the relationship between the dc input voltage and the output magnitude is summarised in Figure 3-8 (b).

Although both modulation methods are important to understand VSI and UPFC's operations, it is seen that PWM has more flexible functions than Square-wave method. The internal control of UPFC for the shunt and series VSI can adopt any of the above methods or their combination. For example, a more economic method for the UPFC is the use of their combination, that is the shunt part of the UPFC uses the square-wave modulation while the series part adopts SPWM. However, to fully make use of UPFC functions, PWM method is the best option for both VSI of UPFC. Because the PWM-based UPFC apparently provides more flexible control ability and also matches the concept of the multiply functions of the UPFC than the square-wave modulation UPFC. Figure 3-9 illustrates the structure by use of PWM for its internal control of UPFC. In this figure, the relations linking to other two states' controllers are also described.

3.3.3 Electromagnetic Transient Studies of UPFC

The electromagnetic transient model of the UPFC depends on its power device configuration, the modulation method adopted. In order to justify the proposed UPFC model, one needs to simulate and analyse it with either digital simulators or analogue-digital analyzers. In general, through electromagnetic transient studies of UPFC, people can evaluate impacts of UPFC on the system. These achievements can include: (i) Understanding UPFC operation theory; (ii) Setting up UPFC internal control scheme; (iii) Calculating the amount of harmonics generated by UPFC and designing filters; (iv) Computing maximum regulating capabilities by UPFC. Furthermore, these studies can provide foundations for designing UPFC and associated protection systems.

Digital simulators are often used for UPFC and other FACTS studies and analogue-digital analyzers are adopted to examine the final implementation of these equipment. SPICE and EMTP are two digital simulation tools widely used in the simulations of power electronics devices. SPICE stands for Simulation Program with Integrated Circuit Emphasis [40]. It is better suited for use in power electronics device models, while EMTP [71] is a very powerful program for modelling power electronics applications in power systems because of the built-in models for various power system components. It is based on this characteristics of EMTP that we will use it to simulate the UPFC model proposed in the thesis. Therefore, the following will focus on in introduction to EMTP as well as other characteristics associated with UPFC switches.

EMTP - Electromagnetic Transients Program - is a full-featured transient analysis program, initially developed for electrical power systems. It is also capable of simulating controls, power electronics, and hybrid situations. The program features an extremely wide variety of modelling capabilities encompassing electromagnetic and electromechanical oscillations ranging in duration from microseconds to seconds. Some main features of it are described as follows:

(1) Types of EMTP studies [72, 73, 74]

The EMTP is used for a wide variety of studies. Some of the important applications associated with power electronics and FACTS applications include :

- HVDC operation and controls
- Various FACTS operation
- General control system analysis
- Protection systems
- Harmonic propagation analysis

(2) Structure of data format of EMTP

Figure 3-10 gives a date file structure combined general data format of EMTP with that of Transient Analysis of Control Systems (TACS).

(3) TACS and selected representation of the GTO device model

In EMTP, power systems transients and control systems could be modelled simultaneously to study their dynamic interaction. "Sensors" pick up signals from the power system (often briefly called the Network) for input to the control system (called TACS). Commands are forwarded from the control system to the power system as shown in Figure 3-11.

The procedure of setting up models of FACTS and the UPFC by EMTP/TACS is to derive mathematical models from the real-world device configurations [75, 76, 77, 78, 79]. For example, the GTO is a key device in the UPFC whose original prototype and characteristics are shown in Figure 3-12 (a) and (b). However, it should be simplified to Figure 3-12 (c) as to match the device type provided by EMTP, shown in Figure 3-13. In this case, the GTO becomes an idealised switch, which can be controlled by signals feedback from the network according to TACS definition. While these signals should be carefully chosen and calculated from the scheme of control strategy. Therefore, from this point of view, modelling, simulation and control of the UPFC is an integrated process.

3.4 Steady-State Modelling and Control of the UPFC

3.4.1 Modelling

There are two types of models representing the steady-state UPFC model [31, 32]. Both are extracted from the prototype of the UPFC concept. One is two voltage sources shown in Figure 3-14, another is one voltage and one current sources shown in Figure 3-15. These two models have no difference in realising the multiply functions of the UPFC. Generally, both models are constrained by some assumptions and relationships between both sources in terms of polar coordinates. Furthermore, those variables representing the UPFC should be limited by internal and external constraints imposed by UPFC and the system.

The functions of the steady-state UPFC model are realised through power flow computations. Thus, implementation of these UPFC steady-state models in power flow algorithms should be completed with taking these model suitability into account. From this point of view, the above model does not consider its compatibility with power flow algorithms and thus it can not directly be implemented in power flow algorithms. Furthermore, those variables representing two-voltage source model of the UPFC are independent and do not give any relations to parameters of the electromagnetic transient model in terms of modulation parameters of SPWM.

3.4.2 Power Flow Methods

Once the steady-state UPFC model is set up, a suitable power flow should be chosen to implement this model. The widely used algorithms are fast-decoupled power flow and Newton method [80]. The theories, algorithms, implementations and practical experiences of both methods have became conventional patterns, in which the use of technologies such as optimal busbar ordering, matrix sparsity and symmetry, liner-equation solutions improve largely the efficiency of the methods. Based on them, there are many modification methods according to some particular problems. Although these power flow methods have evolved into practical applications, there still exists problems of preventing the algorithms from non-convergence. As the UPFC is used to control the system, it often pushes the system to the verge of operational ranges. If the power flow method is not flexible enough to sustain such situations, it is difficult to correctly evaluate performances of the UPFC and its impacts on the system. In this thesis, optimal multiplier power flow algorithm [81, 82] in terms of the rectangular form is adopted as it offers a number of advantages in handling ill-conditioned power flow, including: (i) The optimal multiplier acts as an adaptive gain, which reduces if the Jacobian becomes ill-conditioned. In this way it can give the maximum rate of the convergence at each iteration. (ii) The optimal multiplier power flow method can be used to detect the distance between the desired operating point and the closest unfeasible point. Thus it provides a measure of degree of controllability. And (iii) It can provide computational efficiency without destroying the advantages of the conventional power flow when used together with error-feedback adjustment to implement UPFC model.

3.4.3 Control Methods

As there are many power flow control algorithms which have been developed to furnish such control devices as SVC, phase shifter and TCSC, one needs to understand their different features in order for the UPFC model to be better implemented.

Most general purpose power flow programs contain control facilities to simulate features of real-life power systems. Many of the features to be represented are automatic power system devices operating under single criterion control. The conventional approach to incorporating them in the power flow solution process is to adjust the relevant parameters from iteration to iteration. Two basic ways are Error-feedback adjustment and Automatic adjustment [80]. Nowadays with the evolution of power flow algorithms, user defined model based on the algorithm of error-feedback adjustment to easily incorporate various control parameters has been developed which largely reduce research time.

3.4.3.1 Error-Feedback Adjustment

The Error-feedback adjustment involves modifications of control variables to maintain another functionally dependent objective at a specified value, in a closed-loop mechanism. For example, consider a single criterion control in which a parameter x varies in order to maintain a system quantity w at a scheduled value w^{sp}. The adjustment algorithm takes the form of a closed loop process, where x is corrected at successive power flow iterations, in attempt to reduce the error $w=w^{sp}-w^{calculation}$ below the given tolerance. The adjustment process should not initiated until the power flow calculation has been converged sufficiently to give reliable values for $w^{calculation}$. This adjustment can be used Newton method and Optimal multiplier power flow or any other methods.

The iterative solution process of error-feedback adjustment is briefly explained as shown in Figure 3-16.

In the Figure 3-16,
X: state variables (voltage and angles)
U: control variables (such as the series voltage source of the UPFC)
$W = H(X,U)$: output variables of the objectives of control devices
$F(X,U,D) = 0$: the system equations (power flow equations)
H: functions of the control objectives
D: the system parameters

From the viewpoint of solving U in the diagram, it is predicted that the convergence of this process will not be good. We refer to this process as 'modify control variables without supervision'. Generally speaking, this method is simple and does not need to change conventional algorithms but the convergence speed is slow. However. there are other three methods based on this solution process with the aim to improve the algorithm convergence.

(1) Sensitivity

For

$$W = H(X,U) \qquad (3\text{-}1)$$

$$F(X,U,D) = 0 \qquad (3\text{-}2)$$

Suppose that an initial control variable U^0 and the resulting nominal state X^0 and control objective W^0 are known. That is U^0, X^0 and W^0 satisfy:

$$F(X^0,U^0,D^0)=0 \tag{3-3}$$

$$W^0=H(X^0,U^0) \tag{3-4}$$

If control variable U^0 is perturbed slightly from U^0 to $U^0+\Delta U$, the resulting states and control objective are $X^0+\Delta X$ and $W^0+\Delta W$ which satisfy

$$F(X^0+\Delta X,U^0+\Delta U,D^0)=0 \tag{3-5}$$

$$W^0+\Delta W=H(X^0+\Delta X,U^0+\Delta U) \tag{3-6}$$

Expansion of (3-5) and (3-6) in the neighborhood of the norminal point to the first order of accuracy and eliminating ΔX between the two expanded equations, yields

$$\Delta W=\left[H_u-H_xF_x^{-1}F_u\right]\Delta U=S_{wu}\Delta U \tag{3-7}$$

Where H_u, H_x, F_x, and F_u are Jacobian matrices and S_{wu} is the $(n_w \times n_u)$ matrix of control objective sensitivities with respect to control variables.

Therefore, using sensitivity [83, 84, 85], the error feedback adjustment improves convergence whose iteration process is shown in Figure 3-17.

(2) Distribution factors

In fact, this method originates from the sensitivity method. For example, when any per unit adjustment of control variables U is introduced, it leads to change of the control objective and the relation between them can be expressed in terms of distribution factor D_{wu}. This factor is generally constant, often solved through DC power system equations. The factor is insensitive to operating conditions unlike sensitivity and thus low convergence and inaccurate results are unavoidable. Even though, it is still better than that without supervision. The details of obtaining various distribution factors can refer to [86, 87, 88, 89, 90].

(3) User-defined model

User defined model power flow [91] is widely used in the development of algorithmic power flow software nowadays although it actually is the error-feedback adjustment method. This is because it allows the user to easily construct the models they wish to set up without programming a line of code.

Models for the control of various devices under different objective functions can be constructed using the appropriate user-defined control models. Control models may be built up to match each particular control from a control block diagram. The block diagram is broken up into a number of basic elements. The type of each element, its dynamic constants, the interconnections between elements, and the choice of the system inputs, completely defines the overall steady-state model. The user defined models are flexible, straightforward to set up, and do not require any programming by the user.

The controls may be built from a menu of control blocks, which vary from simple transfer function blocks, through logic and switching blocks, to discrete sampled data type blocks. The system inputs may be the voltages and angles of buses, and line active power, reactive power, power factor or currents and so on.

Although some user-defined model power flow software, such as 'EUROSTAG', 'NETOMAC' and 'UDPSASP' have been developed, more powerful user defined model power flow with easily incorporating FACTS needs to be further developed.

In the physical apparatus, the parameter X, U are either continuously variable quantities or are limited to discrete steps. If in the latter case X and U are restricted to these discrete values during the adjustments, it is not easy to avoid the convergence problems. A typical difficulty is hunting between the various adjustments. A common approach is to ignore discretness in the adjusted parameters until initial overall convergence has been achieved. Only then are the parameters converted to their nearest discrete values, after which the power flow is reconverged with no further adjustments.

In conclusion, the whole computation process of various algorithms of the error-feedback adjustment method is shown in Figure 3-18.

3.4.3.2 Automatic Adjustment

Although the Automatic adjustment method was proposed many years ago by reference [92, 93], until quite recently it has attracted much attention and thus has been revisited due to the development of FACTS devices in power systems. Nearly all papers implementing UPFC steady-state control have used such type algorithms. The method involves modifications of the Jacobian matrix to include the adjustment equality constraints for direct solution of the control parameters, shown in Figure 3-19. Some success had been achieved in the application of Automatic adjustment to the Newton method. This is because Newton method is able to absorb continuous adjustment into the problem formulation, rather than relying on the usual feedback adjustment loops. The adjusted parameters become variables of the main power flow problem, and can be solved for directly by the power flow algorithm. Reference [92] gives the detailed Jacobian matrix of a sample system which contains two load tap changing transformers and one phase shifter. The Jacobian matrix includes two tap settings $\{\Delta t_4/t_4, \Delta t_5/t_5\}$ and one phase shifting angle as variables $\{\Delta F\}$, which can be automatically adjusted.

Reference [92] shows how load tap changing transformers and variable phase shifting transformers may be automatically adjusted by the Newton algorithm, thus complementing a previous inclusion of the area interchange control variables within the Newton algorithm. The method can be extended to consider other FACTS devices.

This method is of fast convergence featured by Newton method. However, Automatic adjustment has two main drawbacks. The first one is that it can not overcome the problem of initial conditions, whose assumptions inevitably require extra iterations or lead to divergence. More seriously, the sparsity structure of the Jacobian matrix is usually altered. To overcome this, the structure of the Jacobian matrix can be altered at the expense of additional programming complexity and loss of efficiency in the triangulation process. These drawbacks have been unavoidably encountered in UPFC applications.

3.5 Electromechanical State Modelling and Control of UPFC

3.5.1 Modelling, Simulations and Control Strategies of UPFC Under Large Disturbances

For the UPFC under electromechanical transient state, the model used often is the steady-state model. This is because its action responding to the system disturbance is quick enough comparing with other devices in the system. Thus, the model of the UPFC under transient state can be regarded as the same as the steady-state phasor model. However, if its model is robust, it should consider the internal response time of the UPFC such as switching instants of both inverter voltage sources as well as PWM strategies. Furthermore, it should be modelled in terms of three-phase form if imbalance, distorted waveform of the UPFC are taken into account.

The time-domain simulation method is necessarily used to validate the model of the UPFC [94, 95, 96, 97]. Many simulation software have been in market and most of them claimed that they can implement the UPFC using user-defined models and achieved preliminary results. However, as the UPFC model and other FACTS devices have some features different from traditional control devices, a transient stability program cannot model their detailed control and system response immediately following a disturbance on account of single-frequency, single-phase modelling. The purpose of modelling FACTS and the UPFC is on account of transient response within the same time frame, possibly in the presence of imbalance, waveform distortion and non-linearity. Even with the prospect of extensive user-defined model [98, 99, 100, 101] adapted for FACTS, large scale modelling capability is limited by lack of precise predictability of FACTS response in the initial period of the disturbance. Once the transient model of the UPFC is set up in such considerations and expressed as three-phase model, the conventional stability simulation methods and software cannot be applied. The compromise often adopted for FACTS and DC transmission system performance evaluation is to derive a functional response from an EMTP solution and to apply it to the equivalent model in the transient stability program [102]. Another way is to develop new algorithms such as the multirate simulation method [103, 104].

Designing the control strategy should consider three main factors affecting performance of the UPFC: (a) Determining the control objective is global or local [105]. (b) Consider the input to the controller globally or locally. (c) Co-ordinate the UPFCs with other FACTS or control devices. Taking these factors into account, one can apply various modern control theories to designing the control strategy, such as optimal control, fuzzy-logic control and robust predictable control [106]. Finally, these control strategies need to be tested by time-domain simulations.

3.5.2 Modelling, Eigenvalue Analysis and Control Design of UPFC Under Small Signal Stability

For small signal stability studies [107], the UPFC model is often derived from linearising its transient model [108, 109]. In this case, many factors such as the internal limits and some control blocks may be ignored around the operating point or the whole linear model are constructed in terms of the piecewise linear forms. It should be noticed that linear UPFC model suits conditions not only of small signal stability (small disturbance) but also of small changes of UPFC control parameters [110, 111].

The UPFC linear model as well as other linear components in the system are often employed eigenvalue analysis method to analyse the system damping for small signal stability and then to provide various system information of detecting the best control point, giving optimal control quantities, which can aid engineers to design different control strategies for UPFC. However, the eigenvalue algorithm for large scale of power systems remains some difficulties. If the system is too big, the computation time of eigenvalue solution will be time-consuming. If the system is too big, it is difficult to analyse the impacts of UPFC control parameters on the corresponding eigenvalues or other systems indexes such as the system damping while these characteristics are important to control strategy design [112, 113, 114].

Based on linear models of UPFC and the system, various modern control theory can be used to design UPFC control strategy. The control strategy can be designed for individual UPFC device or for global FACTS control devices. It should be noticed that selections of various input signals of UPFC controller have significant influence on performance of the designed controller. Generally speaking, control strategies of FACTS devices have limited global impacts on the system stability in the past owing to input signal localisation. With advent of GPS based wide-area signal measurement and micro-wave and optical line based data transmission systems, signals from any remote areas can be collected as the input to controllers. It is reasonably predicted that control strategy of UPFC can be designed for global stability objective through combining its own powerful functions with modern control theory, faster and remote signal collection and transmission

3.6 Summary

Based on the thorough explanations of the operation theory of UPFC in transmission systems, this chapter reviewed various modelling, algorithms or tools and control strategies of UPFC under three operating states. The reviews and comparisons provide useful information for further UPFC research.

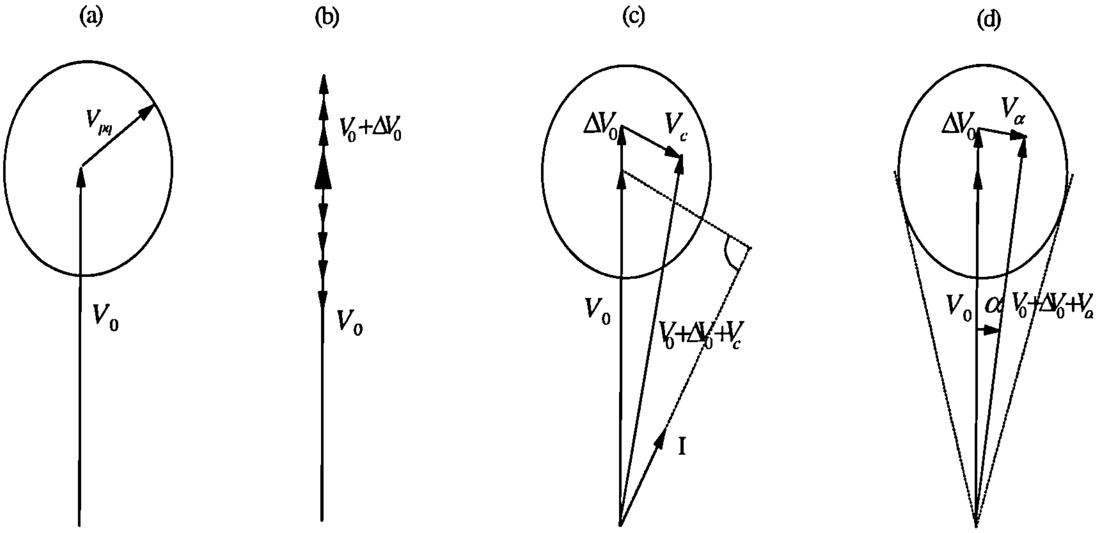


Figure 3-1 Phasor diagrams illustrating the operation of the UPFC

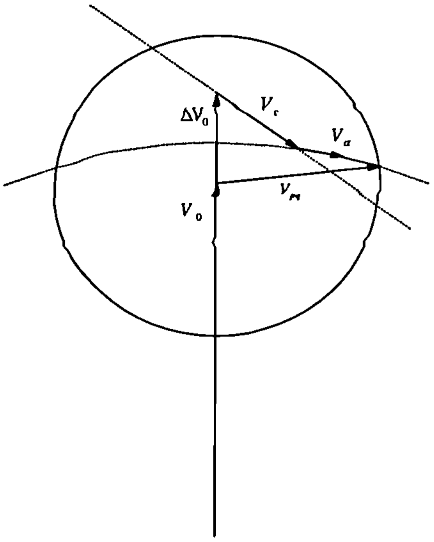


Figure 3-2 Phasor diagrams illustrating the operation of the UPFC

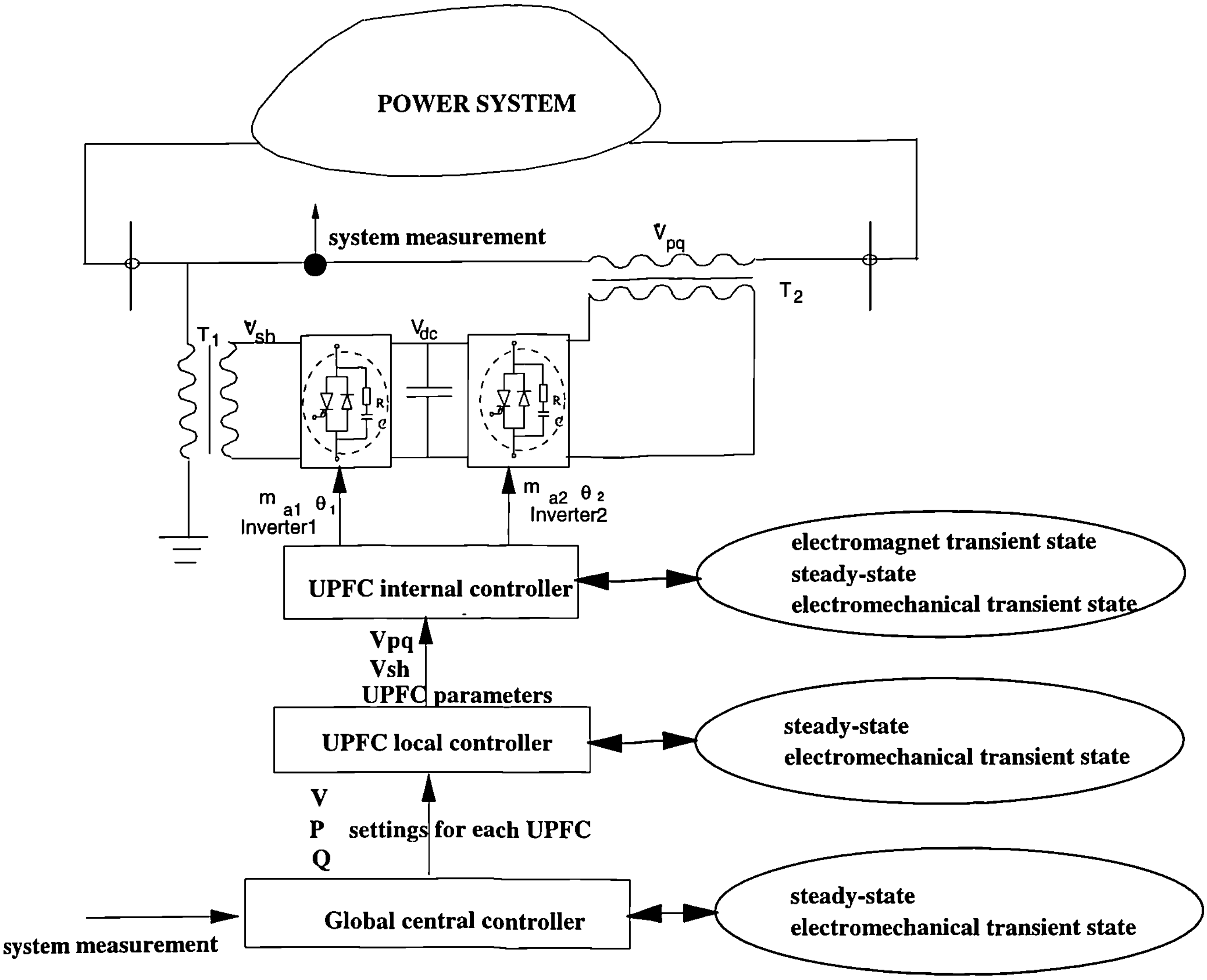


Figure 3-3 Structure of the UPFC modelling and control

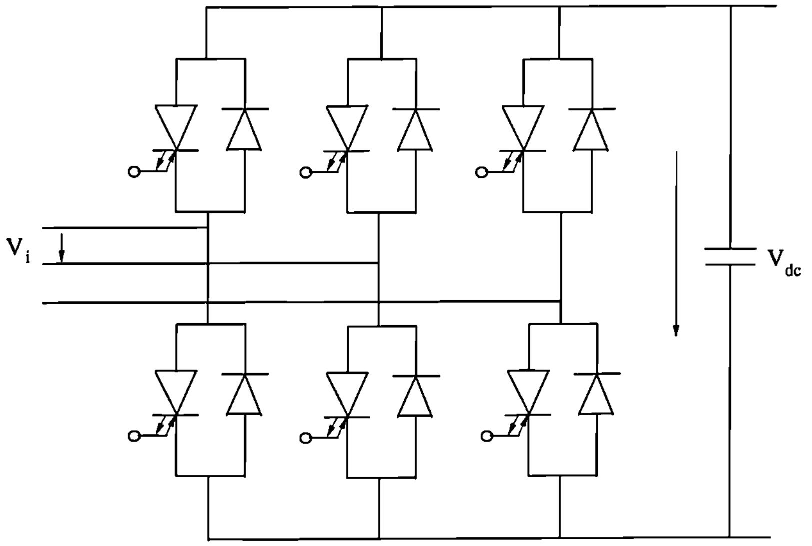


Figure 3-4 Three phase VSI structure

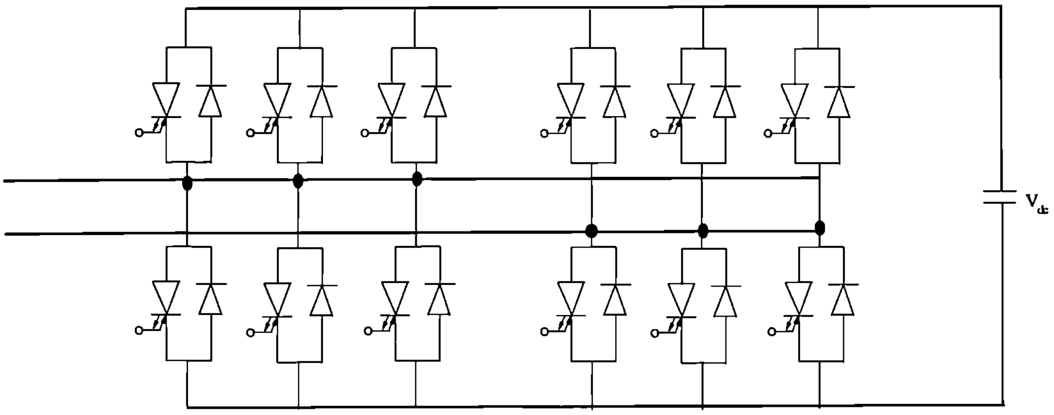


Figure 3-5 VSI in parallel connection

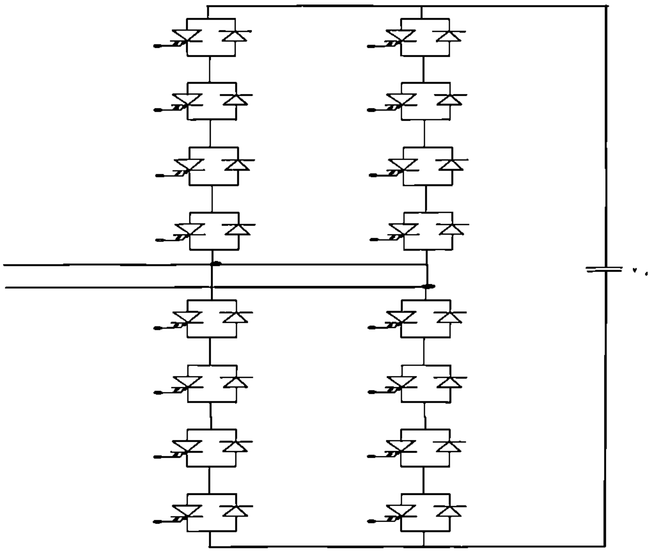


Figure 3-6 VSI structure in series connection

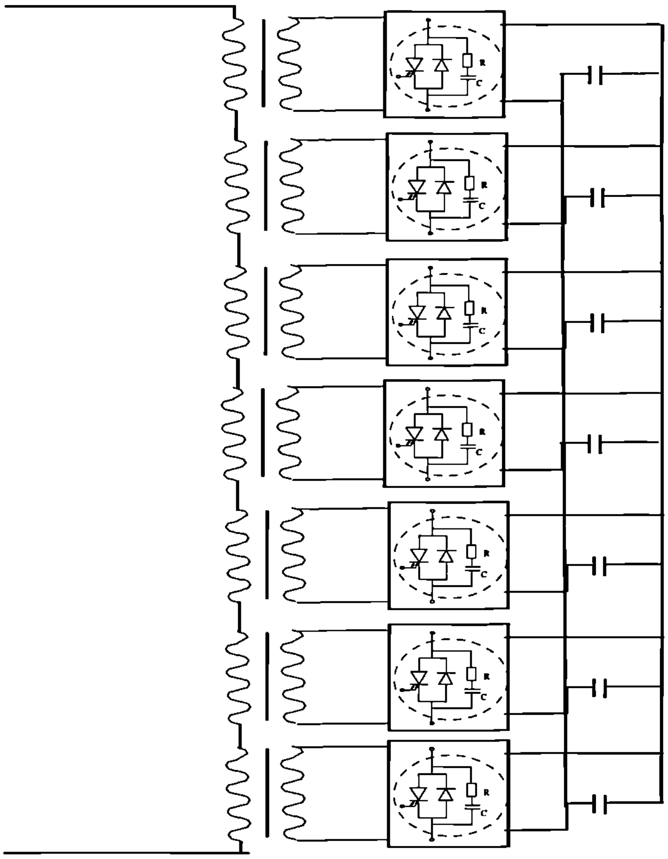
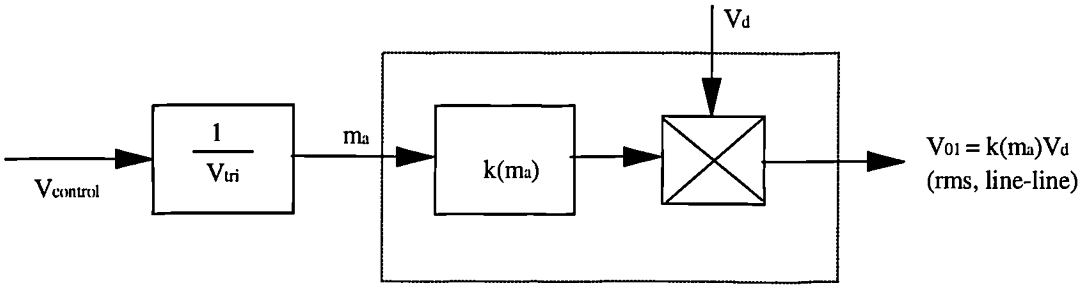
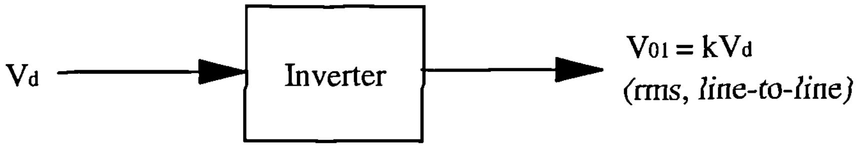


Figure 3-7 VSI structure in parallel/series connection



$$
\begin{aligned}
&\text{for } m_a \le 1.0 \quad k(m_a) = 0.707 m_a && 1-phase\\
&\qquad\qquad\qquad\quad\;\; = 0.612 m_a && 3-phase
\end{aligned}
$$

(a)



$$
\begin{aligned}
k &= 0.9 && 1-phase\\
&= 0.78 && 3-phase
\end{aligned}
$$

(b)

Figure 3-8 Summary of inverter output voltages: (a) SPWM operation ($m_a \le 1$); (b) square-wave operation.

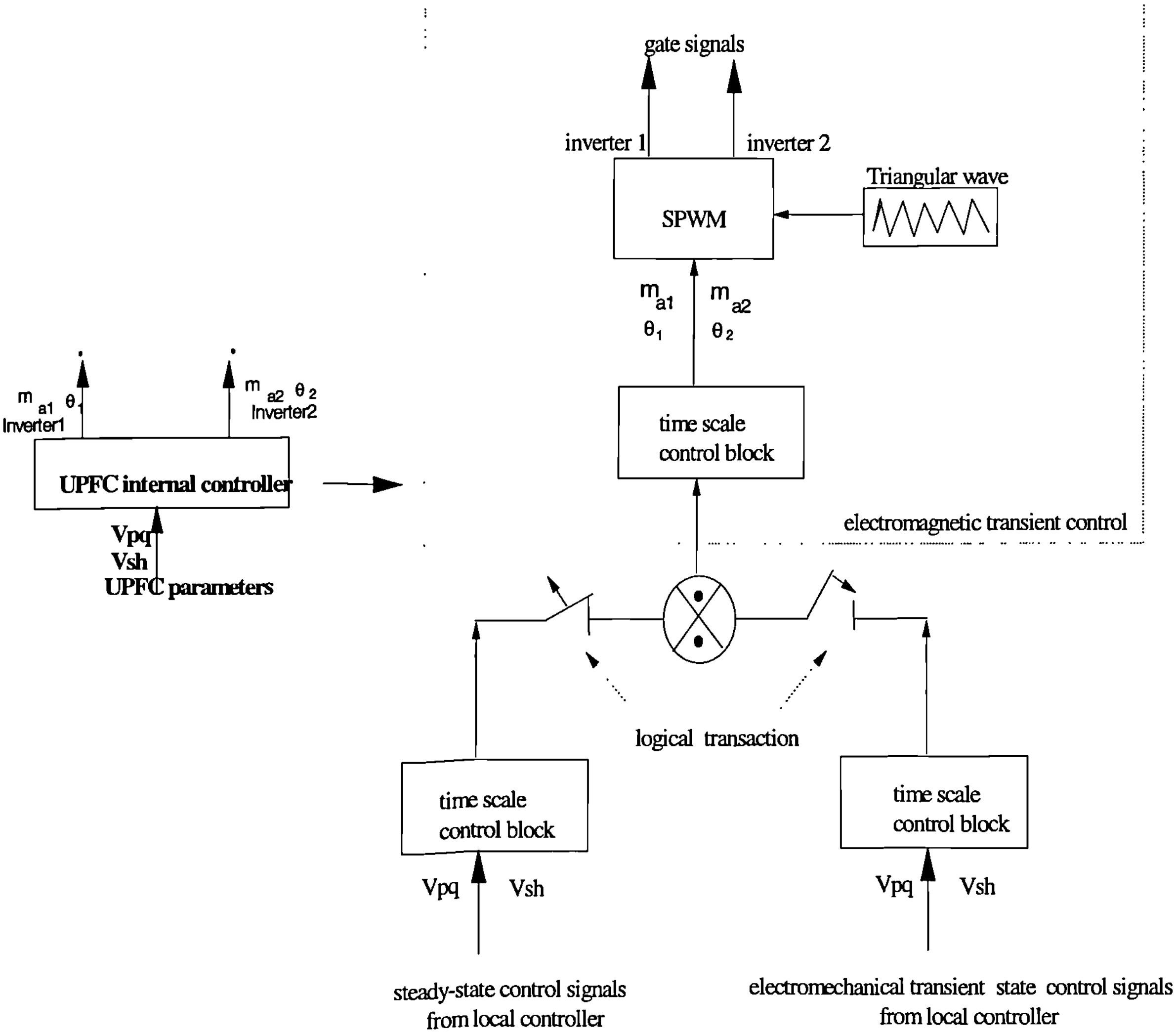


Figure 3-9 Diagram of internal controller structure

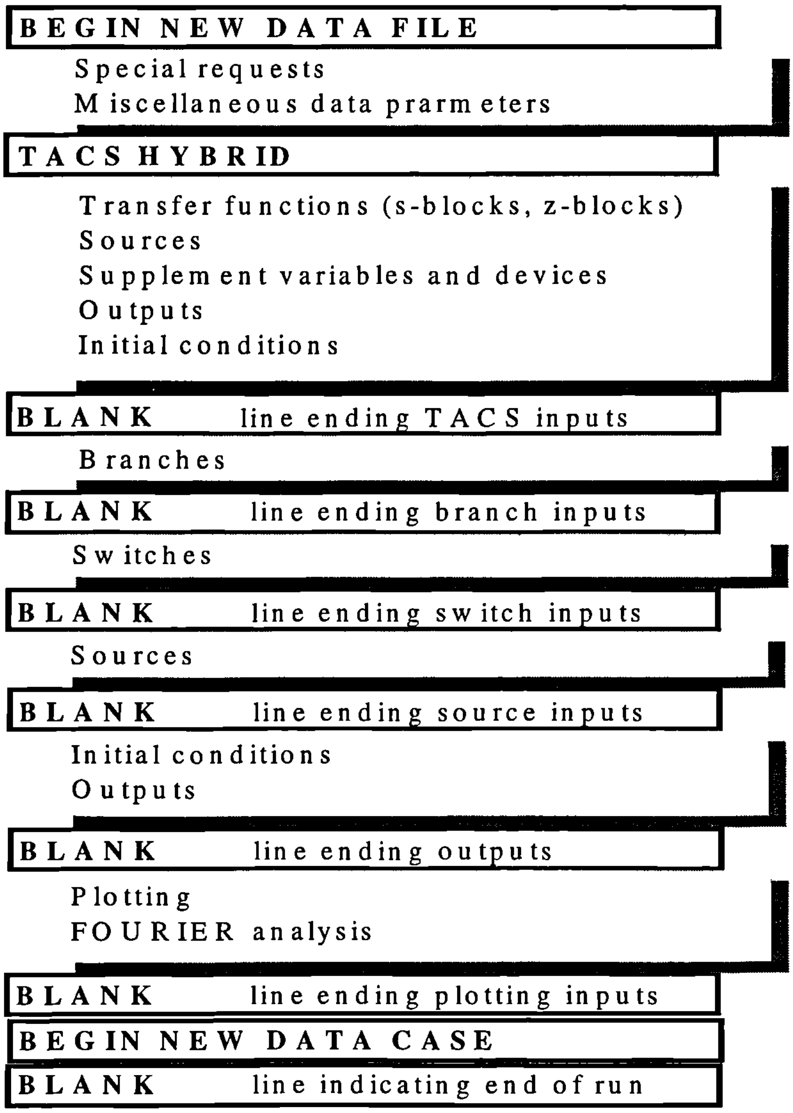


Figure 3-10 Date file structure for EMTP/TACS HYBRID case

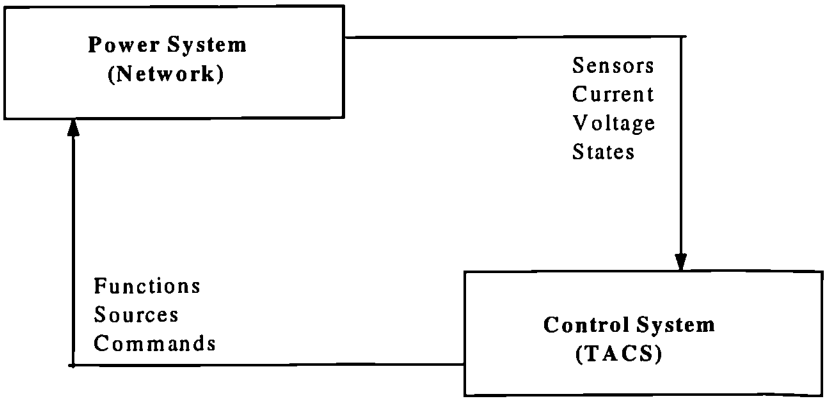
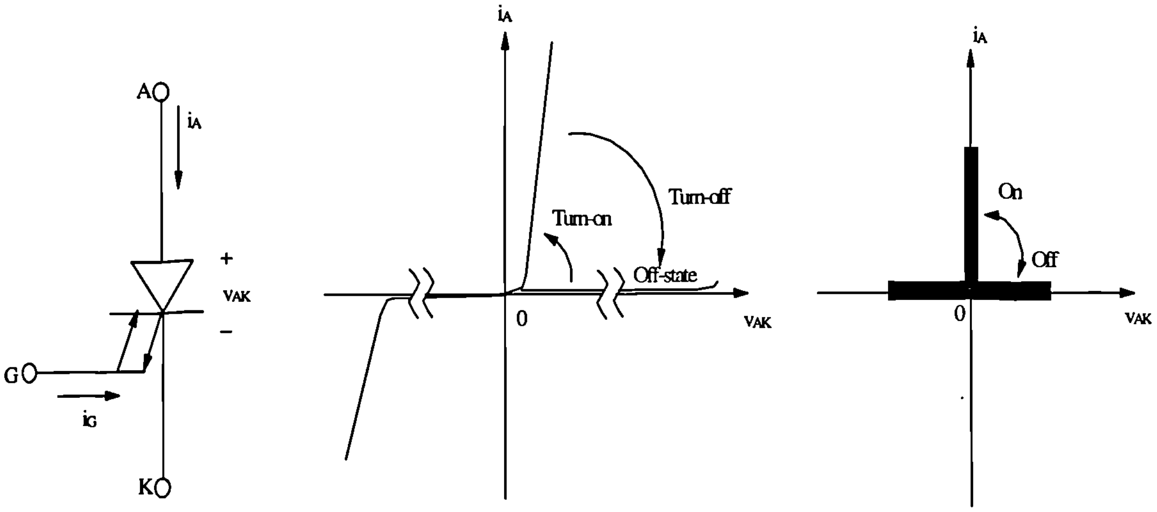


Figure 3-11 Interaction between power system (network) and control system (TACS)



(a) (b) (c)

Figure 3-12 A GTO: (a) symbol, (b) i-v characteristics, (c) idealised characteristics.

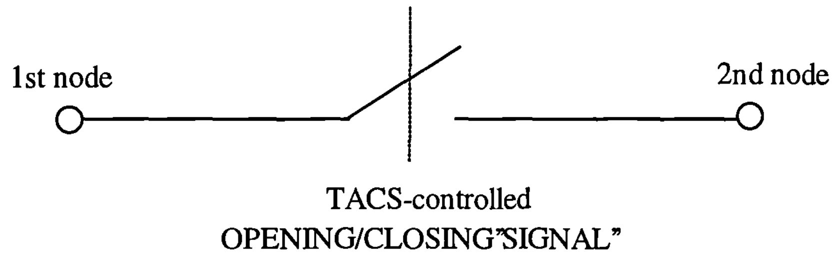


Figure 3-13 Type-11 switch for diode and valve

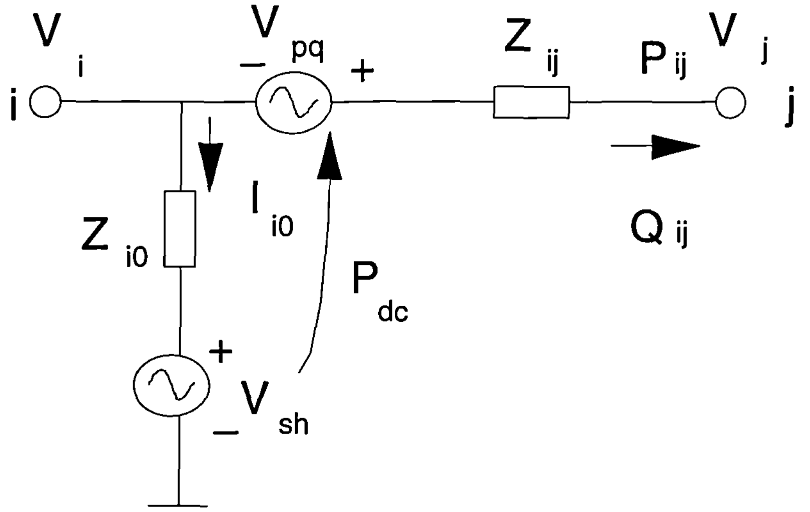


Figure 3-14 Two-voltage source model of the UPFC in steady-state

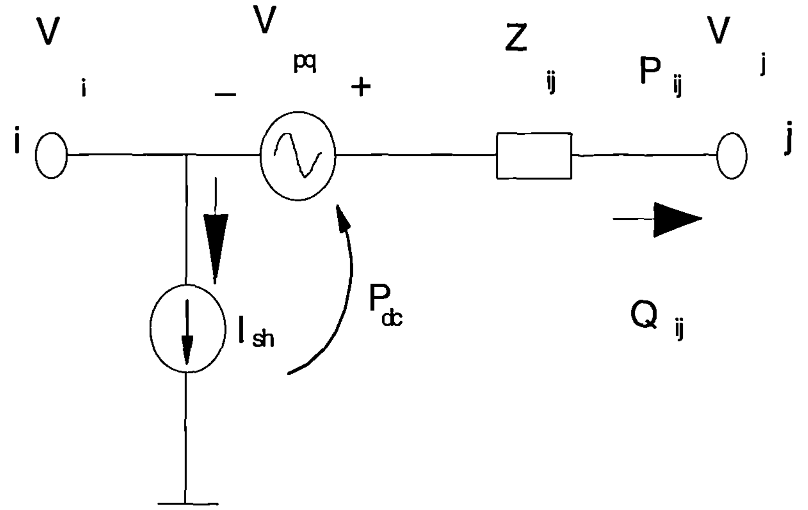


Figure 3-15 One voltage source and one current source model of the UPFC in steady-state

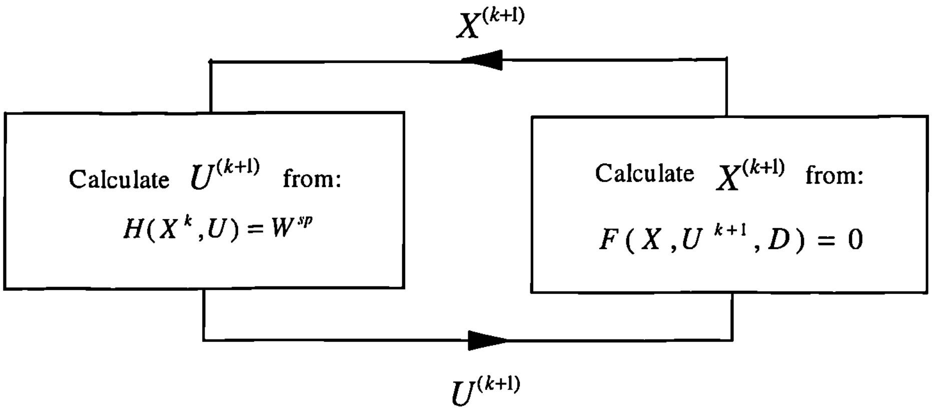


Figure 3-16 Iteration process of the error-feedback adjustment method

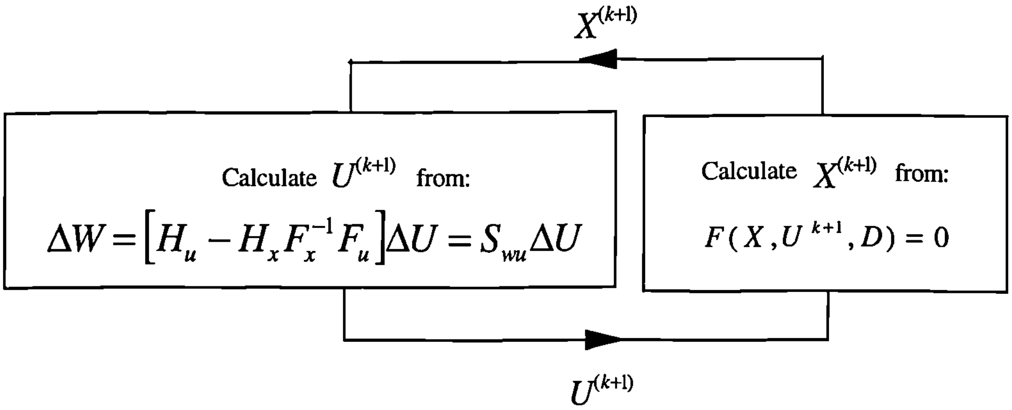


Figure 3-17 Iteration process of the error-feedback adjustment method using sensitivity

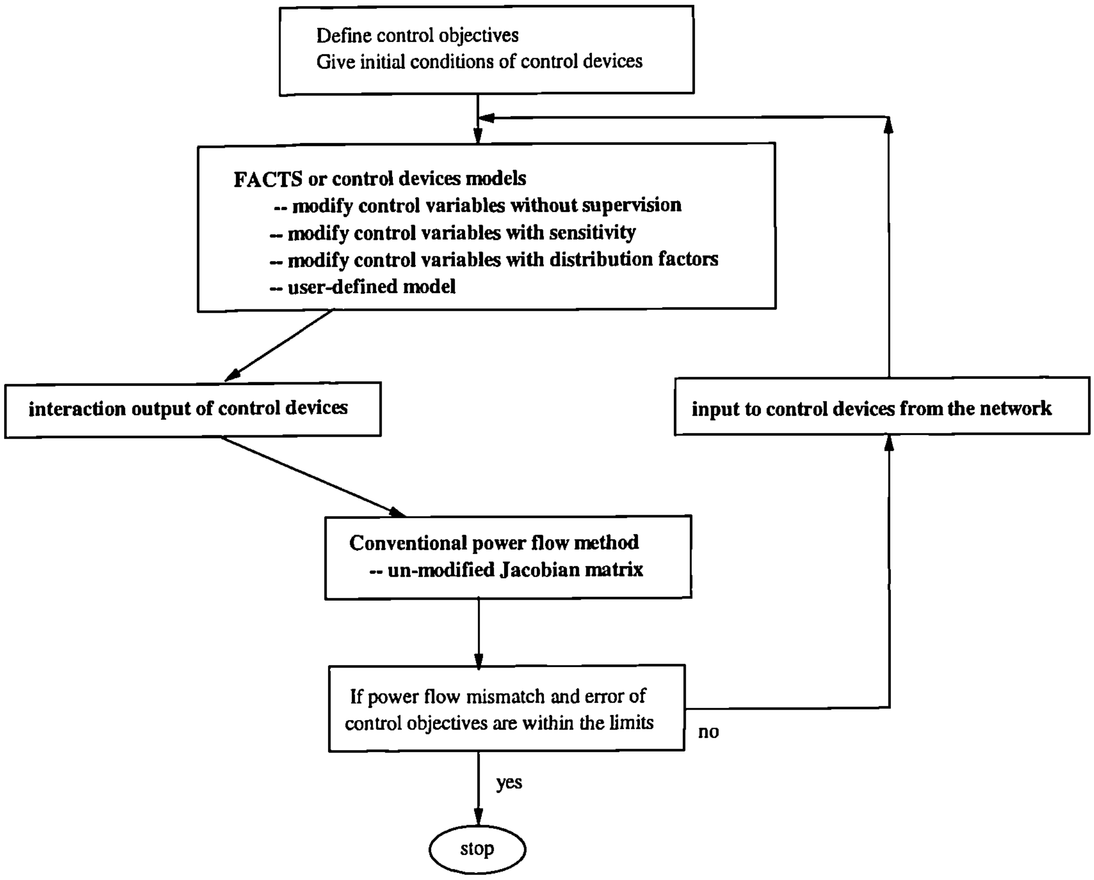


Figure 3-18 Flow chart of the error-feedback adjustment method with control devices

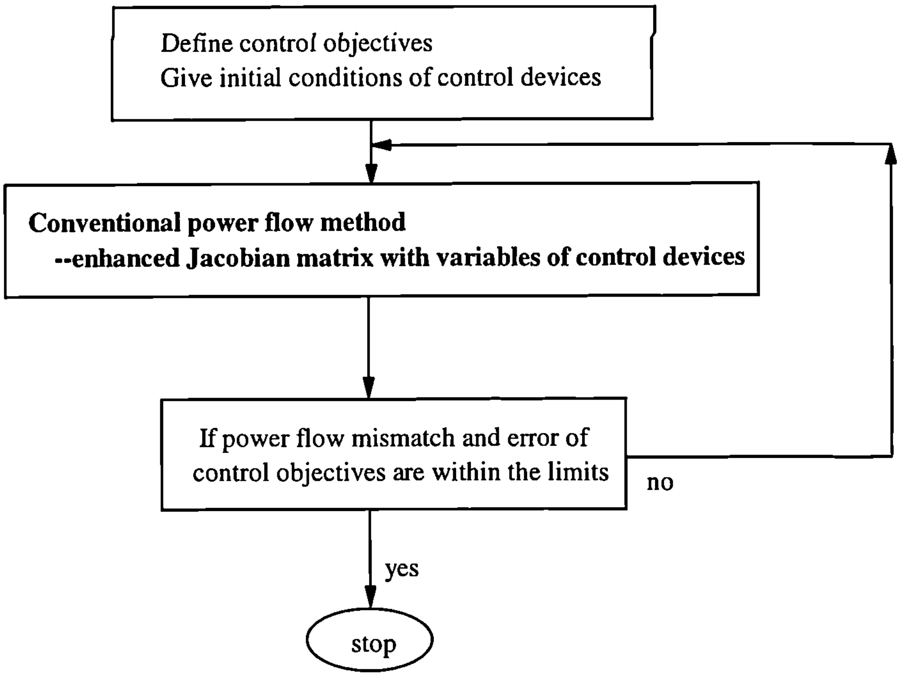


Figure 3-19 Diagram of automatic adjustment method with control devices

ELECTROMAGNETIC TRANSIENT SIMULATION STUDIES OF SPWM UNIFIED POWER FLOW CONTROLLERS

4.1 Introduction

The UPFC can control terminal line voltage, real power and reactive power. Many publications have appeared with emphasis on the understanding of its impacts on the system performances under steady-state and electromechanical transient state. However, few works have been published on the analysis in the equipment level of electromagnetic transient state. It seems to the author that this is very important especially in the practical implementation of such equipment and in understanding its performance.

For simulating the UPFC under electromagnetic transient state, the UPFC model should be set up according to its implementation by use of power electronics devices. Figure 4-1 shows the detailed topology of the two voltage source type bridge inverters, which are distinguished by the following features: (i) The capacitor is across the dc link; (ii) The systems are on the ac side; (iii) Each valve has an antiparallel diode across it. It is assumed that the dc link voltage is always present and sufficiently high with respect to the ac line voltage so that the antiparallel diodes are normally reversed biased. The valves are triggered on and off by logical signals to their gates from the firing control block. This type of the circuit configuration has widely used in various industrial applications such as transportation transaction, machine drives and UPS. While the UPFC using above typical GTO based voltage-source inverters is illustrated in Figure 4-2, in which each inverter leg is composed of a GTO valve and a diode valve in antiparallel connection to permit bidirectional current flow.

In Chapter 3 , two methods have been reviewed, which are often employed to trigger the turn-on and turn-off signals of inverters as the internal controllers: (i) Square wave method; (ii) Pulse width modulated method (PWM). The former is widely used in rectifier and inverter applications and is also considered in the UPFC design. The reference [30] demonstrates the performance of the UPFC employing 48-pulse inverters controlled by square wave method. Although the square wave method shows high quality performance, low harmonic generation and minimum operating losses, it requires more complicated magnetic structure. In recent years, the PWM has been considered to develop new FACTS devices, such as the PWM-STATCON, PWM-HVDC, series-type PWM compensator and PWM phase-shifter [115, 116, 117]. This is because that the PWM inverters have some important characteristics such as [118, 119, 120, 121, 122]:

(1) near sinusoidal current waveforms;

(2) 0--360^0 angle operation;

(3) bi-directional power transfer capability through reversal in the direction of flow of the dc link current;

(4) direct and continuous control of the source voltages on both sides without change of dc-link voltage.

If the PWM method is used in the UPFC, the UPFC will generate low harmonics, require simple magnetic structure, and be relatively inexpensive. Thus the PWM design approach was initially chosen for simulation studies of the UPFC. This chapter will investigate the simple double six pulse inverters with the objective to better understand the basic relationship between the control and functions of the PWM UPFC and to derive useful information for further development and validation of a phasor model of the UPFC.

So far, many PWM methods have been developed with their own advantages in different fields. Generally speaking, the PWM schemes are divided into two groups:

- carrier-based PWM.
- carrierless PWM.

Their characteristics and application in the various area can be found in reference [40]. The carrier-based PWM includes: the sinusoidal PWM scheme (SPWM), the modified sinusoidal PWM technique, the third-harmonic injection PWM technique, and the harmonic injection PWM technique. In particular, SPWM has a number of advantages [69, 70]. The aim of this chapter is to provide the information as to how the inverters are controlled to realize the functions of the UPFC through presenting the performance and capability of the UPFC using the SPWM technique.

This chapter starts with an introduction of the SPWM basic to present the techniques of simulating it by the EMTP. The regulation principle of SPWM inverters for realizing UPFC functions is analyzed and the prototype for UPFC simulation used by the associated EMTP models is constructed. And then it places the emphasis on the detailed EMTP simulation of SPWM UPFC. Before simulation, Fourier analysis method will be used to detect the harmonics of UPFC and then a way to alleviate these harmonics will be developed. Simulation results of SPWM UPFC regulation performance and open-loop control are presented. Based on open-loop studies, the simulator are further used to investigate the operating envelop and closed-loop control.

4.2 SPWM Scheme Generated by EMTP TACS

The SPWM switching is a scheme where a control signal $V_{control}$ (constant sinusoidal wave or varying in time according to control mode) is compared with a repetitive switching frequency triangular waveform, in order to generate the switching signals. Controlling the switch duty ratios in this way allows the average ac voltage output to be controlled. With reference to Figure 4-3 (the diagram is generated by TACS of EMTP according to SPWM theory which will be described in detail in next section), the frequency of the triangular waveform establishes the inverter switching frequency f_s and is generally kept constant along with its amplitude V_{tri}. The control signal $V_{control}$ is used to modulate the switch duty ratio and has a frequency f_1, which is the desired fundamental frequency of the inverter voltage output, recognizing that the inverter output voltage will not be a perfect sine wave and will contain voltage components at harmonic frequencies of f_1. Thus, the amplitude modulation ratio m_a is defined as

$$m_a = \frac{V_{control}}{V_{tri}} \qquad (4\text{-}1)$$

The frequency modulation ratio m_f is defined as

$$m_f = \frac{f_s}{f_1} \qquad (4\text{-}2)$$

Therefore, three parameters are adjusted to adapt the simulation of the UPFC and the system interact:

(1) In order to keep the SPWM operating under linear modulation range, m_a should be from 0 to 1. In this case, $V_{control}$ determines the amplitude of the sinusoidal modulating waveform and therefore modifies the positions of its intersections with the constant amplitude triangular carrier waveform, and hence m_a. $V_{control}$ is generally derived from system control objective, whose amplitude and phase depend on their different requirements.

(2) Because the power system keeps the constant frequency of 50Hz, m_f is chosen as a large number 15 in this case (i.e a repetition rate of 750 Hz), which means that the triangular waveform signal and the control signal are synchronized to each other and the amplitudes of harmonics are small. Therefore, both the frequencies of the $V_{control}$ and the V_{tri} are kept constant during the UPFC operation.

(3) The phase displacement θ between $V_{control}$ and V_{tri} could be regulated according to the demands of the magnitude and direction of power flow. Therefore, two regulating parameters m_a and θ can be employed as internal control to manipulate the turn-on and turn-off signals of two back-to-back inverters of the UPFC.

4.3 EMTP Model Development

The simulation system suitable for electromagnetic study is often adapted as a simple system whose objective value is to understand the UPFC internal regulation concept and interaction with the system. The system adapted includes two three-phase 400kV sources which have a 10^0

phase separation, double circuit 62 km 400 kV transmission line, and the UPFC which is connected to the system at the sending end of the transmission line. This type of 400 kV double circuit is the major type used in the British EHV transmission systems. The whole system contains the necessary components for simulating UPFC, which is implemented in EMTP/TACS data format. Each circuit component has its own associated date input format specified by EMTP manual. Besides these system circuit components, some factors must be taken into consideration in order to operate the system properly, for instance, the snubber circuit is needed to avoid numerical instability of EMTP simulation, power meters are used as the output simulation results and input of closed-loop controllers. The whole list of EMTP model for this system is as follows:

- Sources and transmission lines
- Transformers type: shunt and series
- UPFC and snubber circuit
- SPWM generator for gate firing signals of GTO
- Synchronization
- Power meters and sampling
- Harmonics filters
- Closed-loop control circuits

This section mainly describes how to set up EMTP model of the first six components. The others will be introduced the next several sections.

(1) Sources and transmission lines

(i) EMTP provides many types of sources to be chosen for different studies, such as voltage source, current source and the series voltage sources. These sources can be defined as step, ramp, slope ramp, normal sinusoidal function, given starting and stopping time and phases. In UPFC study, the two terminal sources are specified as the type 14 voltage sources of normal sinusoidal function, whose parameters include: connection bus name, peak value of the amplitude and phase displacement of per phase. There is a defined phase displacement between the two sources to create power transmission.

(ii) The transmission lines use types of the resistance, inductance and capacitance matrix (both symmetrical components and phase components) for the given configuration of overhead conductors through the function of 'LINE CONSTANTS' provided by EMTP. These matrix, the representation of transmission line parameters more detail than that of conventional nominal PI circuit, can easily be inserted into EMTP date file to provide more accurate model of the lines. The input of 'LINE CONSTANTS' includes: tower configuration, skin effect parameter and conductor physical parameters.

(2) Transformer type: the shunt and the series transformers of UPFC

There are two types of transformers used in UPFC EMTP date file. One is the three phase transformer for the shunt transformer of UPFC, whose configuration is wye-wye. Another is the single phase transformer for the series one of UPFC. Both types of transformers can take into account saturation effects. However, no saturation effects are considered for simplicity. The ratio of the primary winding with respect to the secondary winding and the leakage impedance of the winding are the parameters needed to input the format of the transformer type.

(3) UPFC and snubber circuit

The voltage source inverter is the heart of the UPFC. The three phase, full-wave inversion bridge is built using three identical GTO inverter legs. A dc capacitor is the link to the voltage source inverters of the shunt part and the series part of the UPFC. They are represented in the EMTP model by a type-11 diode and a type-11 TACS controlled switch respectively. Type-11 switch can be used to simulate a switch which may be simultaneously controlled by any given TACS variable while following the simple opening/closing rules of a standard diode.

(i) The type-11 switch acts as a diode when the open/close signal is not applied (no TACS control).

(ii) When the open/close signal is specified (the switch acts neither as a diode nor as a valve), type-11 switch is purely TACS-controlled and can be used successfully to model GTO's. A positive signal will result in an immediate closing of the switch and this will remain closed as long as this positive signal is active. It can conduct arbitrary large currents with zero voltage drops. A negative signal will result in an immediate opening of the switch (irrespective of the instantaneous current flow) and this will remain open as long as the negative signal is active. It can block arbitrary large forward and reverse voltages with zero current flow. The change of signal from positive/negative to negative/positive is assumed to be instantaneously when triggered. The trigger power requirement is assumed negligible. In this case, the type-11 switch acts as a ideal GTO, whose signal is from internal control blocks of SPWM.

It is worthwhile to mention the role of the snubbers in the EMTP model. Physically, voltage snubbers are required solely to prevent the switching device from seeing an excessive rate of a voltage change. However, the snubbers shown in Figure 4-4 of this EMTP representation are also for controlling the numerical oscillation associated with the Trapezoidal solution method. As a result, the parameters required for the snubbers in the EMTP model are dependent on the circuit being simulated and the step size selected for the solution. Generally, the minimum RC time constant should be greater than 2-3 times the step size. For this study, simple RC snubber circuits are used, while assuring the numerical stability of the simulations.

(4) SPWM generator for gate firing signals of GTO

To effectively control the UPFC and especially to control GTO switches, it is necessary to model the generation of SPWM signals which are used to trigger turn-on or turn-off of GTO. In this respect, the Transient Analysis of Control System (TACS) (or its equivalent MODELS) of the EMTP provides the way to set up the SPWM switch scheme for controlling the GTO thyristor valves of the inverter. Through using various functions such as the transfer function blocks and FORTRAN-like logical statements provided by TACS, the SPWM control signal where the amplitude and frequency modulation ratios can be changed is shown in Figures 4-3 and 4-5. The SPWM control accepts an analogue sinusoidal modulating waveform signal from each of the 3-phases and an analogue triangular carrier signal, and based on detecting the intersection points it generates gating signals to the GTOs of the bridge. The block labeled $m_a\sin(\omega t+\theta)$ is the key to realize the regulation of SWPM. When m_a, ω, and θ are specified as some values, the UPFC operates under the control of the open-loop controller. When m_a, ω, θ are derived from the system operation and set-points, the UPFC acts under the control of the closed-loop controller. Both cases have their different purposes and will be simulated in next several sections. From the expression, it can be seen that the controlled variable can have a vary large changes on its amplitude and phase in full circle under the control of SPWM.

(5) Synchronization

In the generation of SPWM signals, the phase displacement θ is the ideal phase of controlled variable with reference to the phase of connected bus which is assumed zero degrees. This case is the assumption of the existence of a perfect three-phase voltage source (i.e. infinite bus) right at the point of common coupling (PCC) between the AC and DC system. In technical terms, it can be said that the system interface has an infinite strength, or that it has an infinite effective short circuit ratio (ESCR). However, this is not true in practice because of voltage distortion at the PCC and voltage synchronization problem. For example, the phase of V_0 in Figure 4-6 is not zero and its wave does not always have a pure sinusoidal waveform. The absence of perfect voltage sources at PCC implies the following:

(i) AC voltages at the AC/DC interface will always have some degree of distortion, even with filters installed.

(ii) Three-phase bus voltages at the interface may be unbalanced, say in the event of a single-line-to-ground fault on the AC side.

(iii) As the loading of the system changes, so do the bus voltages. The changes in bus voltages at PCC occur in magnitude as well as phase angle.

In order to successfully obtain the required information on the phase angle Θ of the fundamental AC busbar voltage, a voltage synchronization system is introduced as follows:

Assume AC bus voltage as:

$$V_0 = V_m \cos(\omega t + \Theta) \tag{4-3}$$

Through the use of Fourier analysis:

$$\begin{aligned} C_1 &\equiv \frac{2}{T}\int_{t-T}^{t} v(t)\cos\omega\, \mathrm{tdt} \\ &= \frac{2}{T}\left\{\int_{0}^{t} v(t)\cos\omega \mathrm{tdt} - \int_{\mathrm{t-T}}^{0} \mathrm{v(t)cos}\omega\ \mathrm{tdt}\right\} \end{aligned} \tag{4-4}$$

$$\begin{aligned} S_1 &\equiv \frac{2}{T}\int_{t-T}^{t} v(t)\sin\omega\, \mathrm{tdt} \\ &= \frac{2}{T}\left\{\int_{0}^{t} v(t)\sin\omega \mathrm{tdt} - \int_{\mathrm{t-T}}^{0} \mathrm{v(t)sin}\omega\ \mathrm{tdt}\right\} \end{aligned} \tag{4-5}$$

Note that the above equations can be implemented in TACS with the same concepts as the power meter (whose realization will be described in 'Power meters and sampling ').

V_m can now obtained from

$$V_m = \sqrt{C_1^2 + S_1^2} \tag{4-6}$$

The determination of Θ needs more elaboration. The difficulties arise from the lack of structured IF_THEN_ELSE statements in EMTP. To circumvent the problem, the following expression is suggested:

$$\Theta = a\tan\left(\frac{-S_1}{C_1}\right) + \{C_1.LT.0\} * \pi \tag{4-7}$$

The above expression will correctly return values of Θ ranging from -90^0 to $+270^0$, which generally covers the operation range of the phase for any given bus voltages.

Once Θ is obtained, $m_a \sin(\omega t+\theta)$ can be changed into $m_a \sin(\omega t+\theta+\Theta)$, in which the controlled variable will synchronize with the AC connected bus.

(6) Power meters and sampling

In the EMTP, some functions of monitoring variables have been provided, such as voltages and currents and instantaneous powers. However, more practical interest is the average power over a period of time T sometimes because they are often treated as the inputs to the proposed closed-loop controller of the UPFC. The rate of sampling is also important to the performances of controllers, which is directly related to numerical stability of the controllers.

(i) Power meters

The instantaneous power in any electrical component is given by

$$p(t) = v(t) * i(t) \qquad (4\text{-}8)$$

The average power over a period time T is formulated by:

$$P = \frac{1}{T}\int_{t-T}^{t} p(t)dt \qquad (4\text{-}9)$$

The period of time T is usually one period of the fundamental frequency f. For 50 Hz, the period becomes:

$$T = \frac{1}{f} = \frac{1}{50} = 0.02 \text{ s} \qquad (4\text{-}10)$$

The average power P is constant in steady-state. But the average power varies with time during transients. Then the average power P(t) is of interest during the last half cycle on a continuous basis. It can be found by continuously computing p(t) and splitting the integral into two components.

$$P(t) = \frac{1}{T}\left[\int_0^t p(t)dt - \int_0^{t-T} p(t)dt\right]$$

$$= \frac{1}{T}\left[\overline{P}(t) - \overline{P}(t-T)\right] \qquad (4\text{-}11)$$

The second integral has the value of the first integral delayed by T seconds. This suggests an implementation in TACS as in the figure . The delay of the value of $\overline{P}(t)$ by time T is readily obtained by using TACS Device Code 53 - Transport Delay. Its output value is equal to the input value delayed by time T.

(ii) Sampling and control references

In this EMTP UPFC model, a closed-loop control is accomplished by monitoring the variables to the transmission line and UPFC and then generating gate signals for the inverters to create voltages that will regulate system variables. Sampling of these variables must be at a high enough rate to accurately characterize all variables to be controlled. Then the sampled variables are further processed to sent to the controllers as the practical input. To ensure the accuracy of the overall system modelling and to avoid a possible numerical oscillation, simulation of this entire system involving fast GTO switching actions requires a much smaller time step. If the actual sampling rate is ignored and every calculated point is used for control reference derivation, any interaction between the sampling and the firing control would not be correctly simulated. Since the control response times are so short for the UPFC application, these interactions can be important. The discrete sampling is represented in the model by using a type-58 TACS device to simulate the sampling.

Finally, the diagram including the system, UPFC and its internal control as well system state definitions is shown in Figure 4-6.

4.4 Principles of the UPFC Based on SPWM Inverters

The UPFC proposed for control of active and reactive power in ac systems is typically involved with the use of forced-voltage source six-pulse inverter bridge which is illustrated in Figure 4-6. When the inverter operates under the control of the SPWM, it gives the relationship between the fundamental component of the ac voltage V_{sh} and the direct voltage V_{dc}:

$$V_{sh} = K(m_{a1})V_{dc} \tag{4-12}$$

for $m_{a1} \leq 1.0$, $K(m_{a1})=0.612m_{a1}$, 3-phase

A single phase diagram corresponding to a VSI connected to the utility system through a transformer is given in Figure 4-7. In this case, the general expression for the apparent power flowing between the ac mains side V_0 and the ac side V_{sh} of the VSI is as follows:

$$S_0 = \frac{V_0 V_{sh}}{X}\sin\theta_1 - j(\frac{V_0 V_{sh}}{X}\cos\theta_1 - \frac{V_0^2}{X}) \tag{4-13}$$

Where θ_1 is the phase displacement between V_0 and V_{sh}.

When the shunt part and series part of the UPFC operate under the SPWM, they have different functions. According to the concepts of the UPFC, the functions of the series part are achieved by adding an appropriate voltage phasor V_{pq} to the terminal phasor V_0 as shown in Figure 4-8. Because V_{pq} can be regulated by amplitude and angle, it is important to analyze how V_{pq} is regulated by SPWM. It is assumed that the dc link voltage V_{dc} in the UPFC circuit is kept constant by inverter 1, which can be readily realized by changing the phase angle θ_1 between V_0 and V_{sh}. Therefore, the series voltage output of ac side terminal of inverter 2 can be obtained:

$$\dot{V}_{pq} = T_2 m_{a2} V_{dc}(\cos\theta_2 + j\sin\theta_2)/2 \tag{4-14}$$

where T_2 is the ratio of the series transformer, m_{a2} modulation ratio of inverter 2, and θ_2 is the phase shift angle between V_{pq} and V_0. Thus V_{pq} is defined by m_{a2} and θ_2 and can be proportionally controlled by different m_{a2} and θ_2 according to the concepts of the UPFC which is shown in Figure 4-8. In this way, the UPFC can partially fulfill the functions of voltage regulation, series compensation, phase angle regulation and multi-function power flow control through regulating inverter 2 based on SPWM method.

For the shunt part of the UPFC, it not only provides the active power to charge or discharge the direct link capacitor and keep V_{dc} constant, but also has the function of synchronous solid-state var compensator (SVC), which can control the voltage V_0 through regulating V_{sh}. It is in principle straightforward to meet the requirements of regulating V_{dc} and V_0 simultaneously with SPWM through control of θ_1 and m_{a1} respectively. However, from equation (4-13), the changing of the V_{sh} not only results in the changing of the reactive power flow but also the changing of the active power flow, and can thus lead the changing of V_{dc}. At this time, θ_1 should be regulated in order to keep V_{dc} constant. Under the above assumptions, the inverter 1 has the following operating characteristics:

(1) Active power flow is bilateral. It goes from V_0 bus to V_{sh} bus for lagging θ_1 and vice versa for leading θ_1;

(2) Assuming θ_1 is used to keep V_{dc} constant, the shunt part of the UPFC absorbs reactive power when $V_0>V_{sh}$, which can be realized through decreasing m_{a1};

(3) Assuming θ_1 is used to keep V_{dc} constant, the shunt part of the UPFC supplies reactive power when $V_0<V_{sh}$, which can be realized through increasing m_{a1}.

The SPWM UPFC can thus control transmission line terminal voltage and power along the line by regulating m_{a1}, θ_1, m_{a2} and θ_2 of inverters 1 and 2.

4.5 Fourier Analysis and Simulation Results of Harmonics of the SPWM UPFC

Rapid proliferation of power electronics systems with distorted input currents would have adverse effects, mainly the degradation of the power quality due to distortion in the system voltage provided to other loads. Power systems authorities feel more and more concerned by harmonic re-injection in the network since harmonics cause overheating in transformers, disturbances for consumers, telephone and many other problems in the power system. UPFC naturally generates harmonics. Their level depends strongly on UPFC's structure, inverter control, capacitor size. The injected harmonic can theoretically be reduced to as low level as required, but certain restrictive requirements will have consequences on UPFC's structure and cost.

- The UPFC shunt part injects harmonic currents in the network. If the sizing of UPFC shunt part is negligible versus short circuit power, injected harmonic current would not be significant.

- The UPFC series part injects harmonic series voltages in the transmission line, therefore harmonic currents circulate in a loop formed by parallel lines. Harmonic currents depend on harmonic voltages injected and the impedance of the lines of the loop.

The techniques developed so far to accomplish the above objectives can be categorised into two groups as follows [123, 124, 125, 126]:

(1) Filters to prevent line variable harmonics generated by the power electronics interface from entering the power system. In this approach, the system interface is kept as simple as possible and passive or active filters are used to prevent generated harmonics components from entering the system. Both passive and active filters have their own significant characteristics.

(i) Passive filters attempt to provide a low impedance path for the interface-generated harmonic currents, thus bypassing them from entering the system. This is the fundamental way of handling harmonics which has been widely used because of its low cost and simplicity. However, the passive filter impedance can resonate with the system impedance (which is not well characterised as a function of frequency), thus making the problem of current and voltage waveform distortion even worse.

(ii) In active filters, the distortion component (consisting of various harmonics frequencies) drawn by the power electronics interface is measured and then supplied by a switch-mode power electronics inverter within the active filter. This active neutralisation of the harmonic components is achieved at a substantial cost. Since the distortion component can be almost as large as the fundamental frequency component, the rating of the switch-mode active filter approaches that of the power electronics equipment. Research is continuing on various techniques to reduce the voltage across the active filter in order to reduce its rating and hence its cost.

(2) Waveshaping of the state variables drawn by the power electronics interface to be sinusoidal, thus preventing its harmonic components to be generated in the first place. Magnetics approach is a representative method. In high voltage application, often isolation transformers are needed. Using the 30 degrees phase shift between the wye-wye and the wye-delta transformer connections, a 12-pulse operation is achieved, thus reducing the harmonic content of the input current. This phase-shifting concept can be extended to achieve 18-pulse or even a higher pulse operation to further reduce the harmonic content.

4.5.1 Fourier Analysis

Based on the analysis of the PWM UPFC regulation, this section carries out the analysis on harmonics of the variables of the PWM UPFC. The fundamental frequency components of the voltages at the each side of the UPFC are as follows:

$$(V_{(i.AO)})_1 = \frac{m_a V_{dc} \sin 2\pi f_1}{2} \qquad \text{for } m_a \leq 1.0 \qquad (4\text{-}15)$$

where $V_{(i.AO)}$ is the a-phase voltage at output terminal of the inverter, the suffix 1 is the fundamental frequency component. This equation shows that in a sinusoidal PWM, the amplitude of the fundamental-frequency component of the output voltage varies linearly with m_a. The harmonics in the inverter output waveform appear as sidebands, centered around the switching frequency and its multiples, that is, around harmonics m_f, $2m_f$, $3m_f$, and so on. This general pattern holds true for all values of m_a in the range [0, 1]. Theoretically, the frequencies at which voltage harmonics occur can be indicated as:

$$f_h = (jm_f \pm k) f_1 \qquad (4\text{-}16)$$

that is, the harmonic order h corresponds to the kth sideband of j times the frequency modulation ratio m_f.

However, when we apply above analysis to the investigation of the harmonics of the UPFC, it is much more valuable to directly analyze the harmonics of the variables of interest, such as V_{pq} and V_0 in Figure 4-6, which shows the impacts of the UPFC harmonics on the system. In our analysis and simulation, the THD, acronym for the Total Harmonic Distortion, is used to represent the distortion of the variable. For a periodic function f(x) can be expressed as a series of trigonometric functions

$$f(x) = \sum_{i=0}^{\infty} a_i \cos(ix) + \sum_{i=0}^{\infty} b_i \sin(ix) \qquad (4\text{-}17)$$

where a_0 = dc offset,

$\sqrt{a_1^2 + b_1^2}$ = amplitude of fundamental frequency, and

$\sqrt{a_i^2 + b_i^2}$ = amplitude of i-th harmonic.

Therefore, the THD is

$$THD\% = \sum_i \sqrt{a_i^2 + b_i^2} \qquad (4\text{-}18)$$

The application of the PWM UPFC to the system shown in Figure 4-6 has been used for the simulation studies. The EMTP program gives the waveforms of the variables of interest and the Fouier analysis obtains the harmonic results of the relevant values. The following is two sets of some typical open-loop simulation results, which do not have filters at the each side the UPFC:

CASE 1: $\theta_1=-20^0$, $m_{a1}=1.0$, $m_{a2}=0.8$, $\theta_2=90^0$

CASE 2: $\theta_1=-18^0$, $m_{a1}=0.8$, $m_{a2}=0.8$, $\theta_2=90^0$

Table 4-1 is the list of the THD values of the V_0 and V_{pq} under two cases. From the second row of the table it can be seen that V_{pqTHD} is ten times higher than V_{oTHD}. Figures 4-9 and 4-10 demonstrate the harmonic spectrum of relevant variables under case 2, which shows that the various harmonics is corresponding to theoretical analysis of the $(jm_f\pm k)f_1$. For example, the 5th, 7th, 11th, 19th and 23th harmonics are all agreement with the law. The V_{pq} waveform of the Figure 4-11 verifies the distortion of the V_{pq}.

From the above simulation results and analysis, it is seen that PWM UPFC produces the harmonics injected to the system, which leads to the poor quality of the system operation. Therefore, it is necessary to install the filters to attune the harmonic impacts of the UPFC.

4.5.2 Filter Design and Its Effects

Harmonic voltages generated by shunt inverter and series inverter are similar. In case of harmonic pollution of the system by the shunt part, the parallel filters are adopted. Concerning the series part, the main consequences of harmonic rejection is a circulation of current in the loop where UPFC is inserted. To meet the specification on harmonic currents circulating, other special filters may need to be developed. However, the objective in our research is to demonstrate the filter effects on preventing the harmonics generated by the UPFC entering the system and correcting the distorted waveshapes of the variables. Thus, the filter type designed is similar to that of passive filters. The passive filters are generally shunt-connected branches that present a low impedance path to ground for harmonics. They also appear as large capacitors at fundamental frequency, thus providing all or part of the needed reactive power compensation.

For our simulation system, we design two tuned filters and one damped filter for one side or both sides of the UPFC, which is shown in Figure 4-12. The actual filter parameters used are given in Table 4-2. Figures 4-13 and 4-14 demonstrate that our resultant AC filter has low impedance value at 5th and 7th harmonic frequencies. It also appears as a low impedance with some damping over a wide range of frequencies.

In order to demonstrate the filter's effects on the harmonics of the UPFC, we investigate the above two cases under two conditions:

- Only the shunt side of the UPFC is installed with a filter;
- Both the shunt and the series sides are installed with filters.

The last two rows of the Table 4-1 give the simulation results. Figures 4-15 and 4-16 are the waveforms of V_{pq} and its relevant variables. Figures 4-17 and 4-18 are the harmonic spectrum of the V_0 and V_{pq} under case 2 with filters. V_{pqTHD} with filters is reduced to half of the situation without filters. The whole harmonics is lower than before without filters. All these results show that the filters installed the series side of the UPFC have direct and great effects on the harmonics of the UPFC, and reduce the THD value and improve the quality of the V_{pq} thus realize the functions of the UPFC.

4.6 Open-Loop Simulation Results of SPWM UPFC

In this section, simulation results through detailed modeling of the UPFC based on SPWM inverters by EMTP are presented. The SPWM switch scheme for controlling the GTO thyristor valves of the inverters has been set up using TACS of the EMTP, in which the SPWM control signal can be generated according to the open-loop simulation or the closed-loop control studies. The application of the SPWM UPFC to the system shown in Figure 4-6 has been used for the simulation studies. The following is two sets of some typical open-loop simulation results:

(1) Simulation of SPWM UPFC regulation performance

(i) The first group results only consider the series part of the UPFC and the V_{dc} is kept to 65kV. When V_{dc} is kept constant, V_{pq} is regulated through the changing of the m_{a2} and θ_2, which are shown in Figures 4-19 ~ 4-22. When the system operates only with the control of the series injected voltage, it can be clearly seen from Figures 4-19, 4-20, 4-21 and 4-22 when θ_2 is changed from 0^0 -- 360^0, the V_{pq} rotates according to the analysis of Figure 4-8. And when m_{a2} decreases the V_{pq} also reduces which is shown in Figure 4-23.

(ii) The second group results mainly concern the shunt part of the UPFC. When V_{dc} is kept constant to be 65kV in the case through regulation by θ_1, the V_0 is controlled through regulation by m_{a1}, which are shown in Figures 4-24 ~ 4-26. When the UPFC connects to the V_0 bus, the shunt part of the UPFC can compensate the reactive power needed by the system in order to increase V_0 or absorb the reactive power to decrease V_0. From these Figures, different conditions which show the leading or the lagging compensation are presented. When m_{a1}=0.8, there is no exchange of reactive power and V_0 and I_a are thus in the same phase. When m_{a1}=1.0, the compensation is maximized and I_a thus leads V_0. When m_{a1}=0.6, the inverter absorbs the reactive power and I_a thus lags V_0.

(2) Results of the power flow and voltage support under control of SPWM UPFC

When V_{dc} is kept constant, the amplitude and phase of V_{pq} can be regulated to control the line power flow. In these cases corresponding to Figures 4-19 ~ 4-22, the double circuit transmission line power flow is effectively controlled, which are shown in Table 4-3. The phasor of V_{pq} related to others also shows that δ between V_r and V_L as well as the magnitude of V_r qualitatively reaches maximum at $\theta_2=90^0$ which transfers maximum P, but when $\theta_2=180^0$ the δ remains the same and the magnitudes of both V_r and P decrease under m_{a2}=1.0. When V_0 is controlled by the shunt part of the UPFC, UPFC acts as a STATCON to give the voltage support. Its impacts on power flow can be also found in Table 4-4 which corresponds to Figures 4-24 ~4-26.

(3) Operating Envelop of UPFC

Based on a large number of simulation results and analysis, the operating envelop of the UPFC at the specified condition can be deduced. Generally speaking, it is difficult to define the operating envelop of the UPFC because all four parameters of m_{a1}, θ_1, m_{a2} and θ_2 will couple together to affect the regulation of the SPWM UPFC. As to the normal operation of GTO valves, it often keeps V_{dc} at a minimum voltage under which the valves will extinct. In this case, it is easy to obtain the operating envelop of power vs. m_{a2} and θ_2 of series part and the full operating envelop of the UPFC at the V_{dc}=65kV, which are shown in Figures 4-27 and 4-28.

From Figure 4-27, it can be seen that P and Q can be regulated within a wide range only with the control of m_{a2} and θ_2. Figure 4-28 appears that the operating envelop of power will be extended when inverter 1 also takes part in regulating.

4.7 Design and Simulation of Internal Controller of UPFC

An internal controller of the UPFC has been designed for preliminary evaluation studies [127]. In this respect, the UPFC controller is designed as a proportional-integral feedback type controller which is shown in Figure 4-29. In Figure 4-29, X_{input} represents the variable from the system to be controlled, such as active power of transmission line and voltage of dc-link capacitor. $X_{reference}$ is the desired value. PI-type function is the conventional structure. The limiter forces the SPWM operate in a linear range. Y_{output} is one of inputs of control signal in the SPWM, that is m_a, or θ or ω in Figure 4-3. All UPFC internal controller in Figure 4-6 has the same structure as in Figure 4-29.

There are three control parts of UPFC:

(1) The PI controller for the series part of the UPFC is to control θ_2 to follow the variation of P under the condition that m_{a2} is kept constant. The P from the system is measured through scaling factor and compared with the reference value. Through PI-type function, the error between the reference and the measured is regulated to null. Generally, the modulation index m_{a2} can also be used to regulate active power P of transmission line. However, the regulating range of m_{a2} to the P is narrower than that of θ_2 from Figures 4-27 and 4-28. So the θ_2 is chosen to control P only. In this case the capability of the series part is maximum if $m_{a2}=1.0$. It is important to notice that reactive power Q of transmission line can not be controlled decoupling with P through either m_{a2} or θ_2, which means that P can be controlled to the desired value through θ_2, meanwhile the Q is forced to follow the path defined by Figure 4-27.

(2) The PI controller of the shunt part is to keep V_0 constant by regulating m_{a1} while PI control of θ_1 is to regulate V_{dc}. In this case, the shunt part plays two roles in the operation of UPFC: one is as dc voltage regulator using θ_1, which must convert the same amount of active power to replace the power that has been drained by the series part placed across the dc link;

another is reactive power generator using m_{a1}, which can generate or absorb reactive power form full leading to full lagging in order to increase feasible range of connected-bus voltage.

(3) The dc side capacitor must remain properly charged in order for both parts of the UPFC to operate according to control objectives. V_{dc} and V_{deref} are the monitored and the pre-set dc voltage, respectively. The two signals are compared and the difference is magnified through a PI controller. The output θ_1 of the PI controller is modulated with a sinusoidal signal synchronised with the system and hence regulating dc voltage through charging or discharging the dc capacitor.

Three PI controllers need to be designed to have a wide feasible solutions according to the operating envelop of the UPFC shown in Figure 4-27 and 4-28. However, it should be pointed out that such PI controllers of the UPFC designed only demonstrate the functions of the UPFC. For example, the PI-type function of P-θ_2 should be designed to achieve any desired P within 0^0--360^0 according to Figure 4-29. But the PI-type function in our design can only operate within 0^0--180^0 of θ_2. So other design methods are needed to realize required functions.

In order to demonstrate the performance of the controller, three simulation results are shown in Figures 4-30, 4-31 and 4-32 where $P_{simulation}$, $Q_{simulation}$, P_{ref}, $V_{0simulation}$, and V_{0ref} represent phasor quantities, *θ_l and θ_2 are outputs of PI functions, and P_{err} and V_{dcerr} are the error to be* controlled to null. Therefore, three cases are used to test the control functions of these controllers:

Case 1: In Figure 4-30, the V_{dc} and V_0 references keep constant during the simulation, and the references to the P changes from one steady-state to another at the time of 0.1s. With the control of θ_2 tracing the change of P, P_{err} is quickly controlled to null during control period although P jumps 820,000 kW from 585,000 kW at 0.1s. In this case, θ_l used to maintain dc voltage constant nearly keeps unchanged.

Case 2 : In Figure 4-31, the reference to the V_{dc} varies at 0.1s while V_0 and P keep constant. Using PI-type control, V_{dc} can easily and much quickly modulate with great change of the reference value.

Case 3: In Figure 4-32, only V_0 changes with the time, in which I_a becomes from lagging to unity related to V_0.

In conclusion, it can be clearly seen that under these different conditions the UPFC is effectively controlled to trace the variations of the system, and the transient process from one steady state to another state is very short, within several cycles. In the closed-loop control demonstrations of PI-type function, the problems of power flow control and voltage support are also solved simultaneously. The whole control process is stable and the controller is robust and operates under different scenarios.

4.8 Summary

This chapter has described some research results of EMTP-based digital studies of SPWM UPFC. Useful insights into UPFC performance have been attained through the detailed analysis and simulation of the UPFC internal structure and the regulation method. The voltage and power control simulation results have demonstrated the functions of the UPFC. Studies have also indicated that PWM is a potentially promising method for the effective regulation of the UPFC.

The whole process of setting up EMTP based UPFC model has been discussed in detail: Firstly, SPWM scheme generation and the main factors affecting the functions and all aspects concerning with the model have been mathematically explained. Secondly, how the series part and shunt part of the SPWM UPFC are controlled and coordinated has been analyzed. Simulation results of SPWM UPFC regulation performance and open-loop control have been given to validate the described theory. The simulator has further been used to investigate the operating envelop and closed-loop control. This EMTP-based simulator of SPWM UPFC implemented has provided a useful tool to assist the development and validation of more detailed and practical model of the UPFC for further studies.

Table 4-1 List of THD values

case	case 1		case 2	
	V_{oTHD} (%)	V_{pqTHD} (%)	V_{OTHD} (%)	V_{pqTHD} (%)
without filters	1.76	17.20	1.63	16.10
with shunt filter only	0.39	17.19	0.85	16.20
with shunt and series filters	0.50	8.60	0.50	8.45

Table 4-2 List of filter parameters

Type	Tuned	Tuned	Damped
h	5th	7th	11th
R (Ω)	1.27	0.90	70.92
L (mh)	107.42	54.81	13.16
C (μF)	3.77	3.77	6.36

Table 4-3 List of regulating parameters and power under different cases (the series part of the UPFC)

case	m_{a2}	θ_2 (degree)	P (MW)	Q (MVar)
1	0.8	0	459	411
2	0.8	90	990	-250
3	0.8	180	0	-200
4	0.8	270	-350	390
5	1.0	90	1169	-337
6	0.6	90	761	-127
7	0.4	90	552	-55

Table 4-4 List of regulating parameters and power under different cases

case	m_{a1}	θ_1 (degree)	m_{a2}	θ_2 (degree)	P (MW)	Q (Mvar)
1	0.6	-15	0.8	90	860	-290
2	0.8	-18	0.8	90	950	-250
3	1.0	-20	0.8	90	990	-250

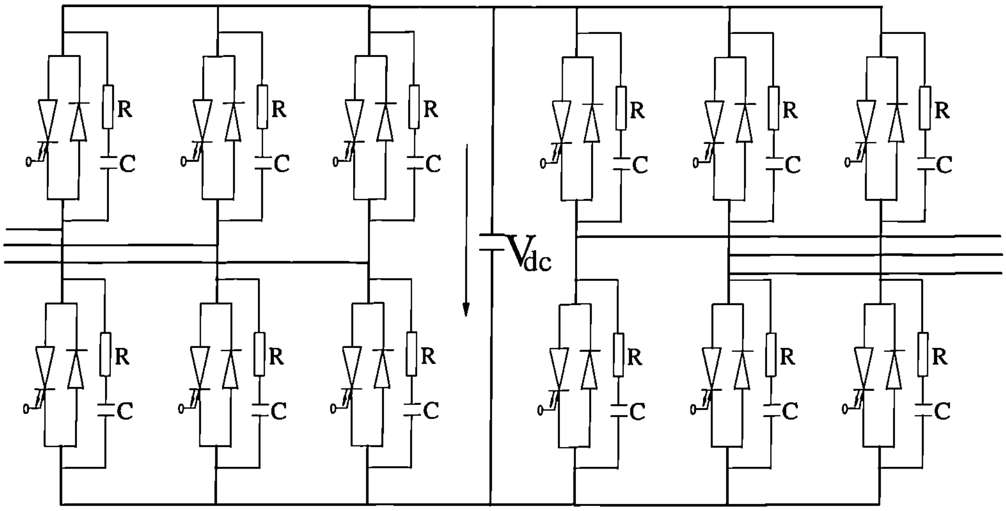


Figure 4-1 The internal relations between two forced-voltage source six-pulse inverters through dc capacitor

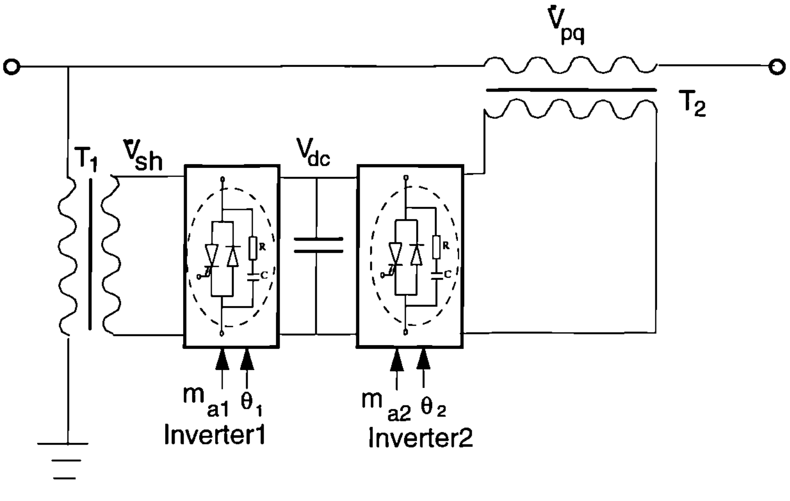


Figure 4-2 Arrangement of UPFC

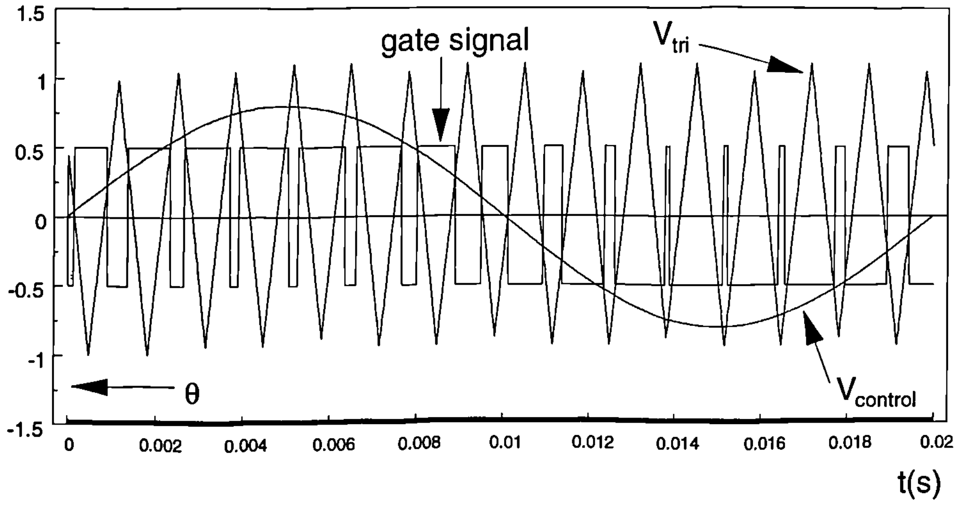


Figure 4-3 PWM signal generated by TACS

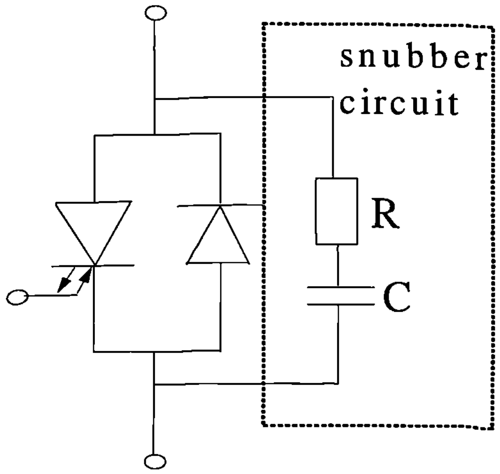


Figure 4-4 Diagram of circuit on every bridge of VSI-inverter

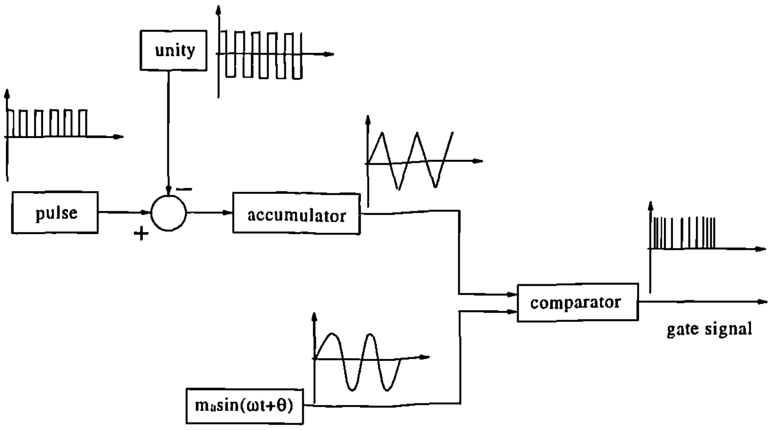


Figure 4-5 Transfer function of TACS to generate gate signal of the inverter

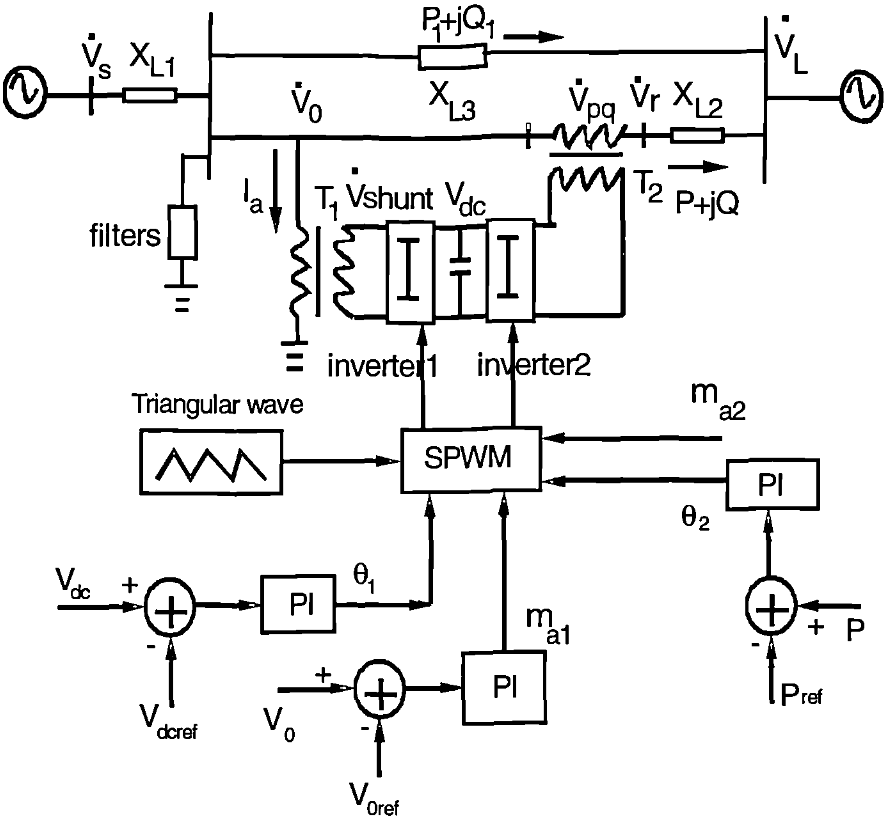


Figure 4-6 A EMTP UPFC model in a simple system with the control of UPFC

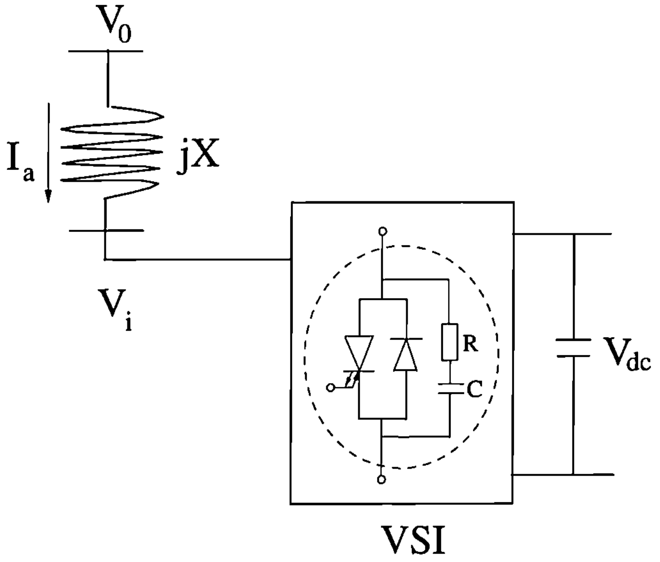


Figure 4-7 A single diagram corresponding to a VSI connected to the utility system through a transformer

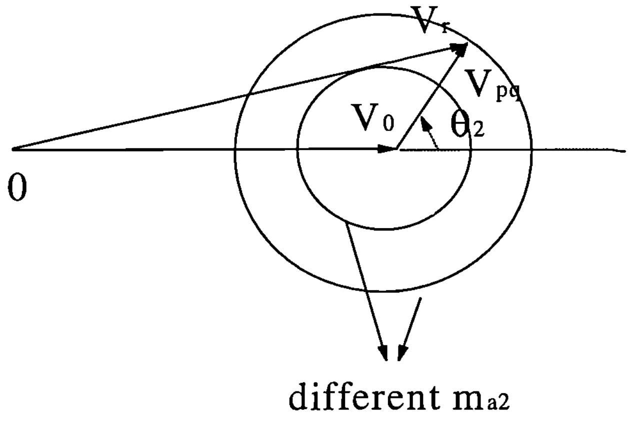


Figure 4-8 Phasor diagram of multiple control scheme

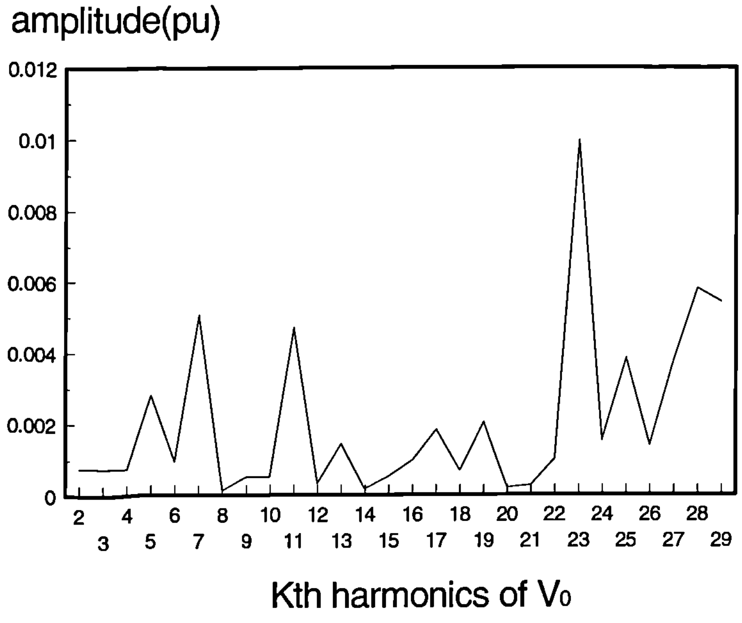


Figure 4-9 Harmonic spectrum of V_0 without filters under case 2

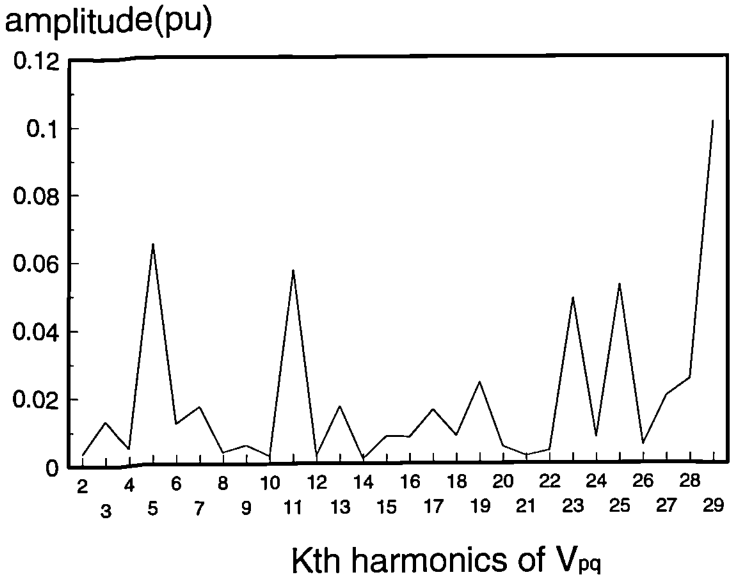


Figure 4-10 Harmonic spectrum of V_{pq} without filters under case 2

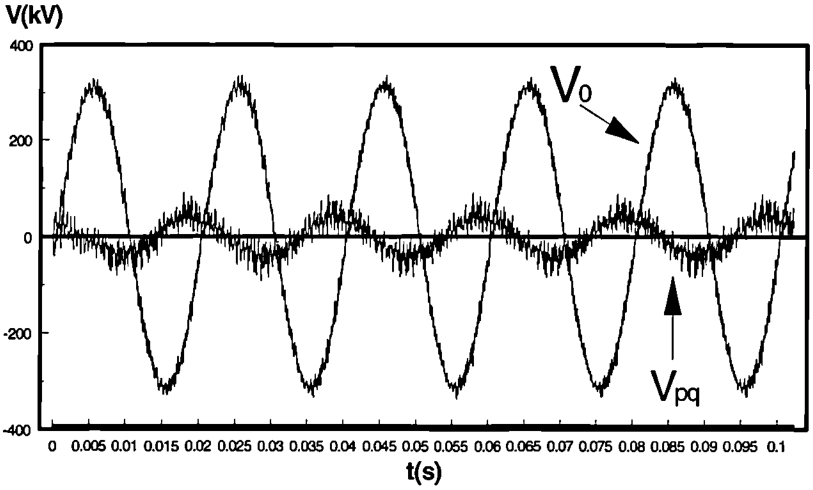


Figure 4-11 Waveforms of variables without filters under case 2

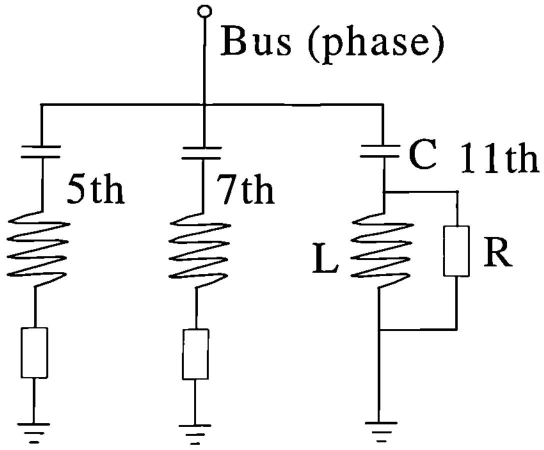


Figure 4-12 Arrangement of the filter

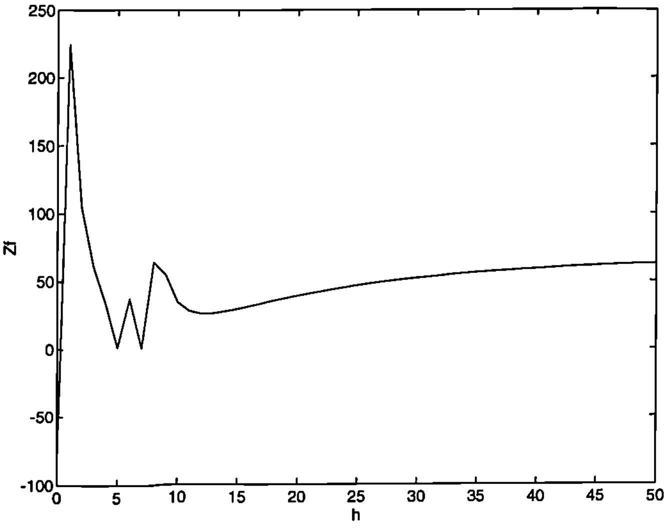


Figure 4-13 Magnitude of filter impedance vs. Frequency

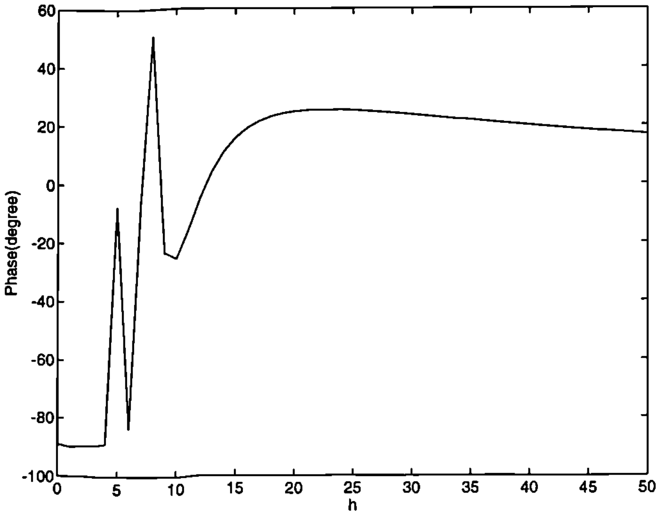


Figure 4-14 Angle of filter impedance vs. frequency

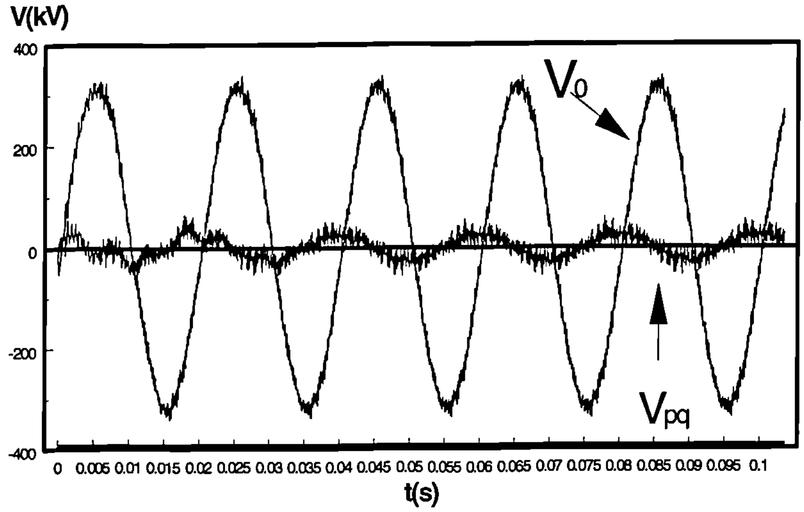


Figure 4-15 Waveforms of variables with the filter only at the shunt side under case 2

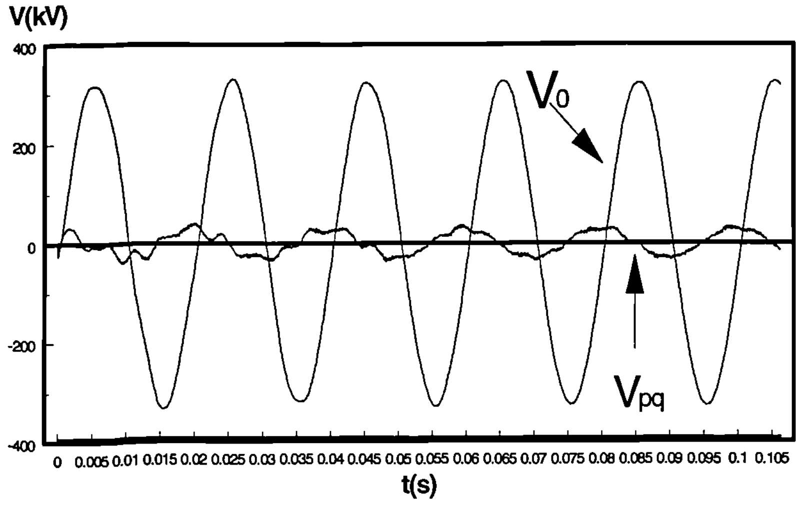


Figure 4-16 Waveforms of variables with filters at both sides under case 2

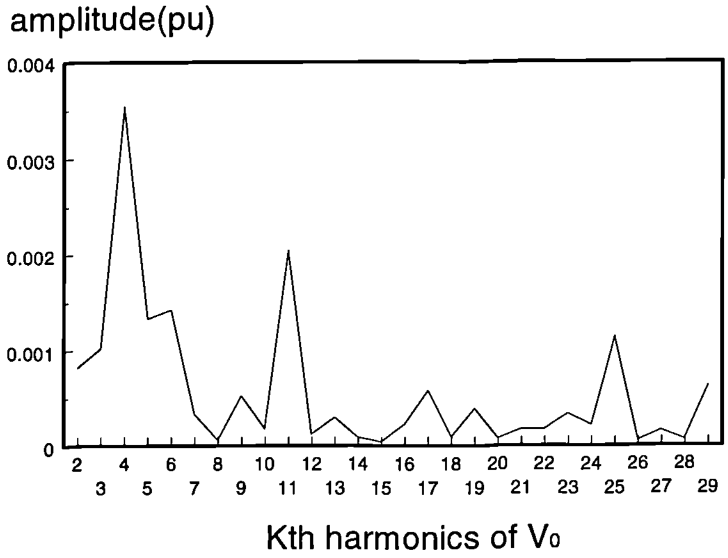


Figure 4-17 Harmonic spectrum of V_0 with filters at both sides under case 2

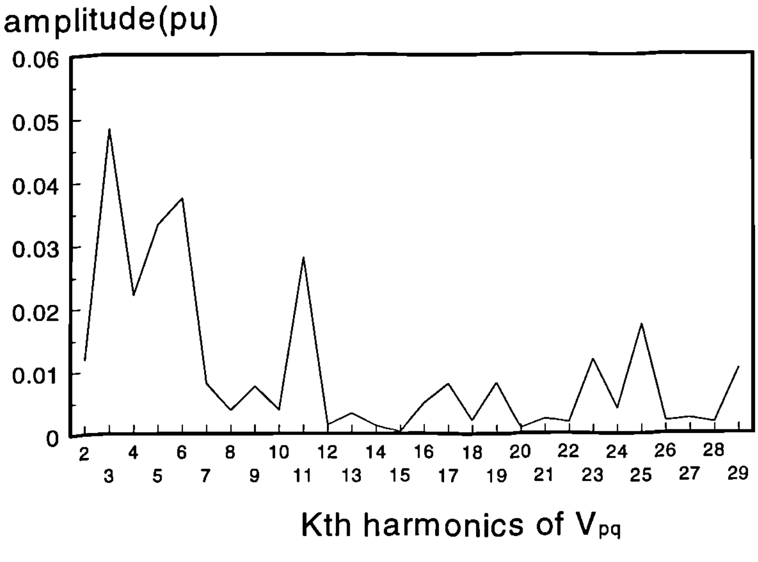


Figure 4-18 Harmonic spectrum of V_{pq} with filters at both sides under case 2

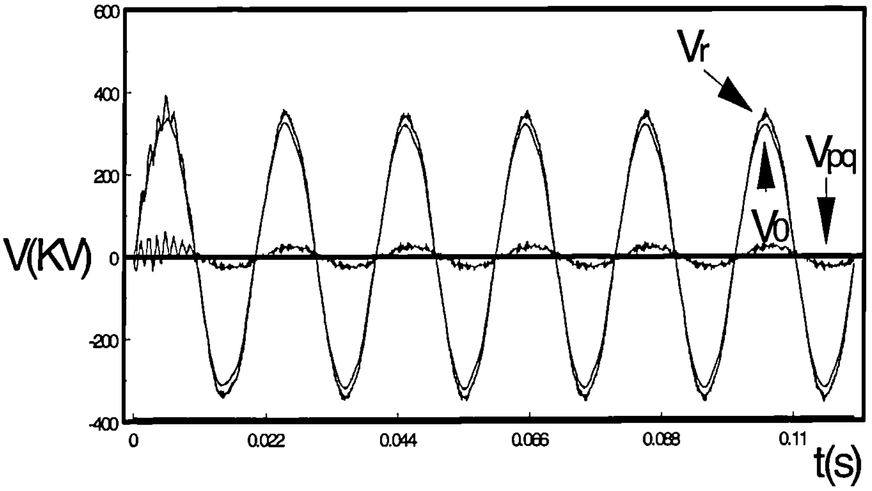


Figure 4-19 Simulation results of V_0, V_{pq}, and V_r when V_{dc}=65kV, m_{a2}=0.8, and $\theta_2=0^0$

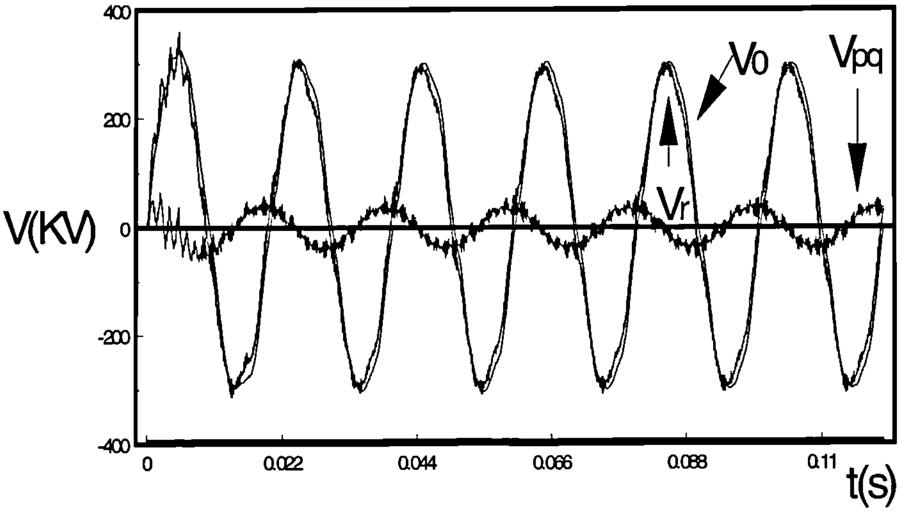


Figure 4-20 Simulation results of V_0, V_{pq}, and V_r when V_{dc}=65kV, m_{a2}=0.8, and $\theta_2=90^0$

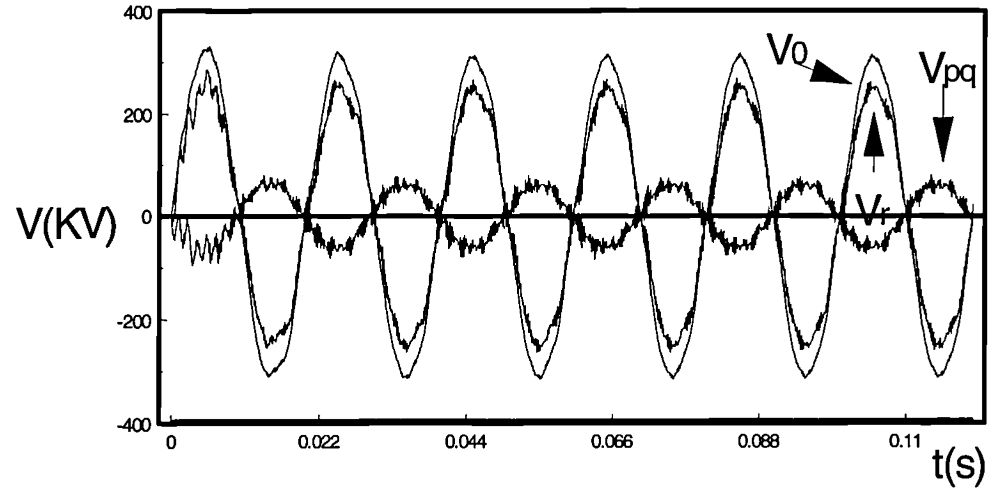


Figure 4-21 Simulation results of V_0, V_{pq}, and V_r when V_{dc}=65kV, m_{a2}=0.8, and $\theta_2=180^0$

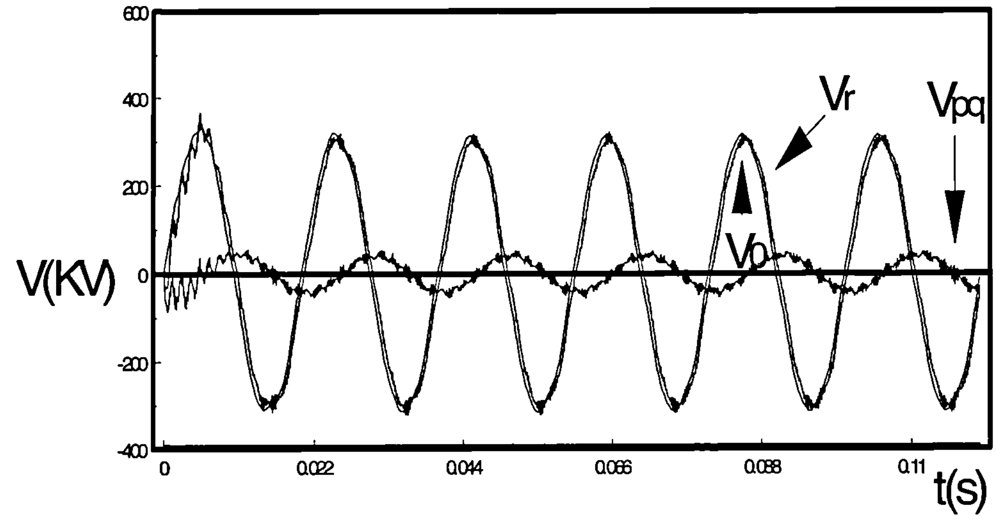


Figure 4-22 Simulation results of V_0, V_{pq}, and V_r when V_{dc}=65kV, m_{a2}=0.8, and $\theta_2=270^0$

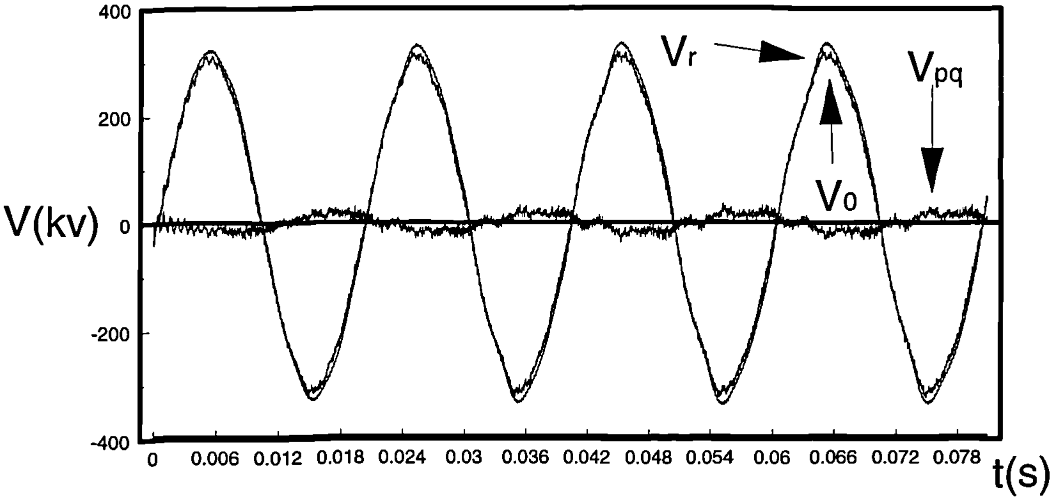


Figure 4-23 Simulation results of V_O, V_{pq}, and V_r when V_{dc}=65kV, m_{a2}=0.4, and $\theta_2=90^0$

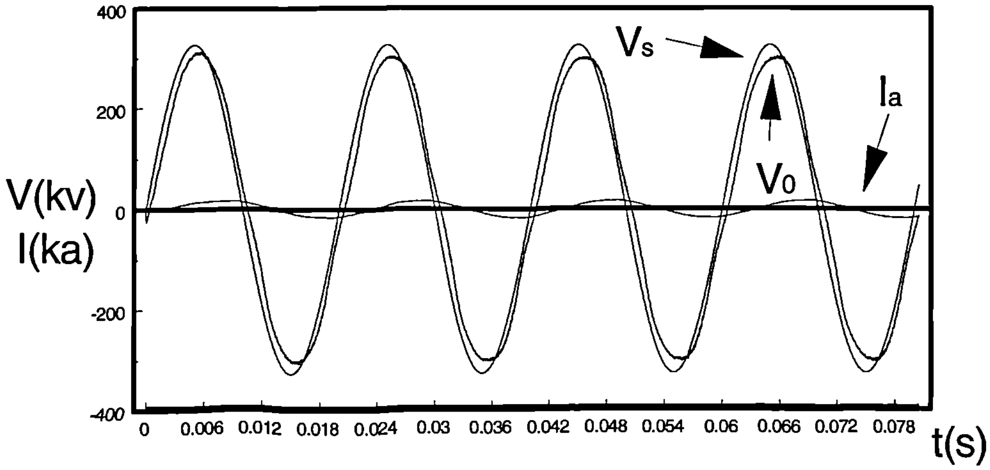


Figure 4-24 Simulation results of V_O, V_s, and I_a
when m_{a1}=0.6, V_{dc}=65kV, m_{a2}=0.8, and $\theta_2=90^0$

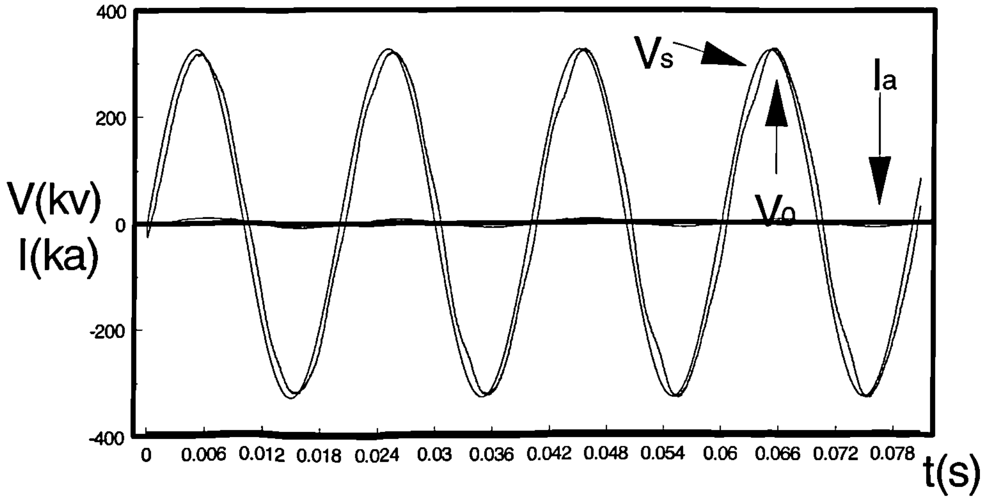


Figure 4-25 Simulation results of V_O, V_s, and I_a when $m_{a1}=0.8$, $V_{dc}=65kV$, $m_{a2}=0.8$, and $\theta_2=90^0$

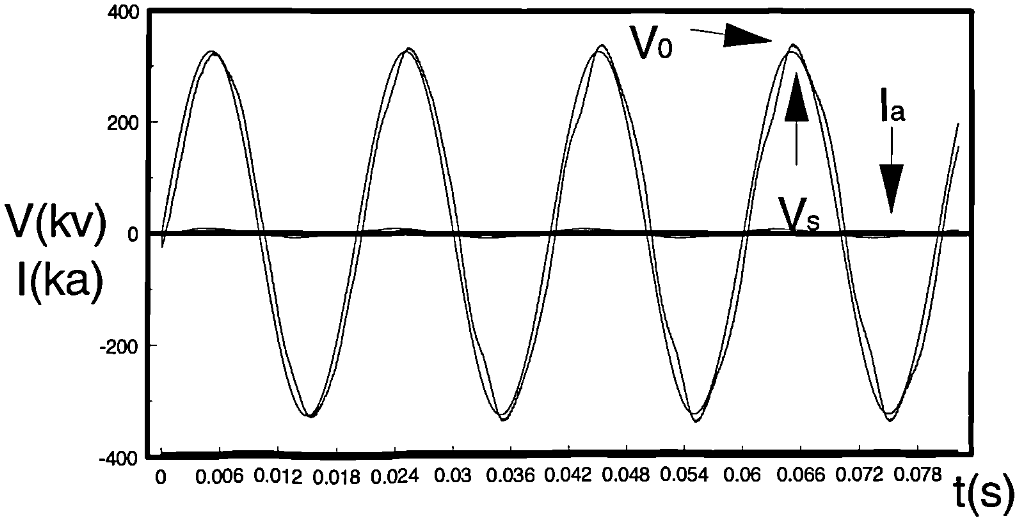


Figure 4-26 Simulation results of V_O, V_s, and I_a when $m_{a1}=1.0$, $V_{dc}=65kV$, $m_{a2}=0.8$, and $\theta_2=90^0$

Capability of the UPFC

(only series part considered)

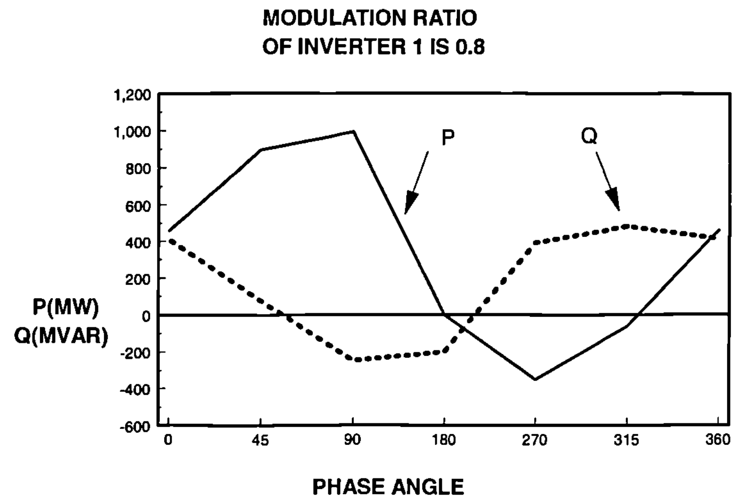


Figure 4-27 Operating envelope of the series part

Full capability of the UPFC

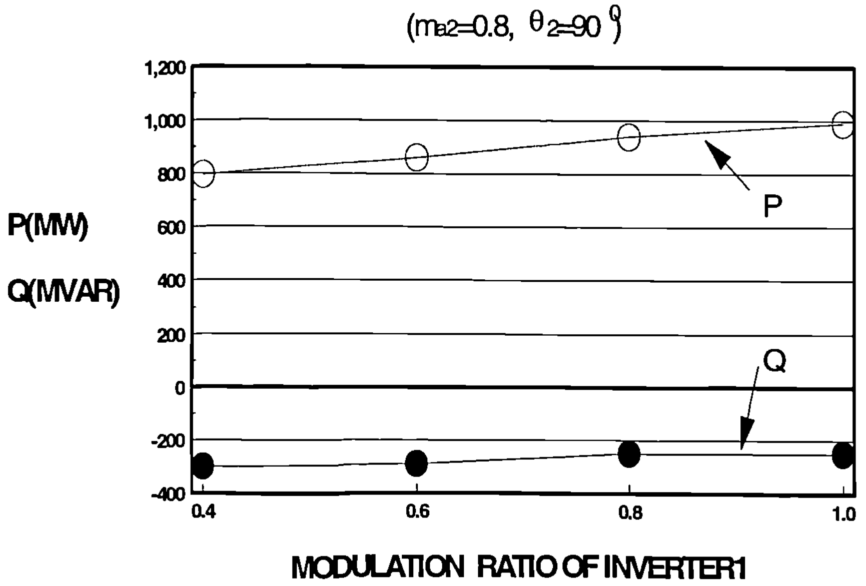


Figure 4-28 Operating envelope of the UPFC of the series part of the UPFC by PWM regulation

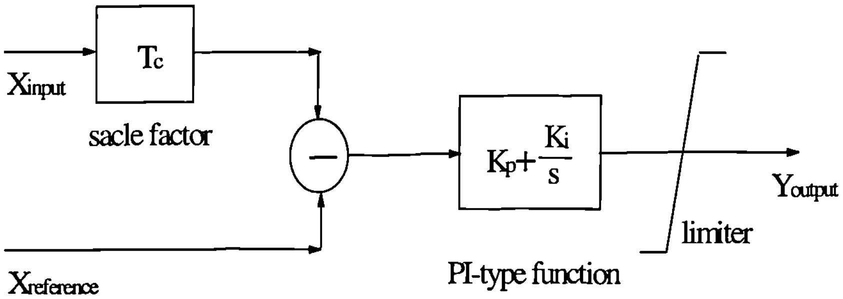


Figure 4-29 PI-type function block

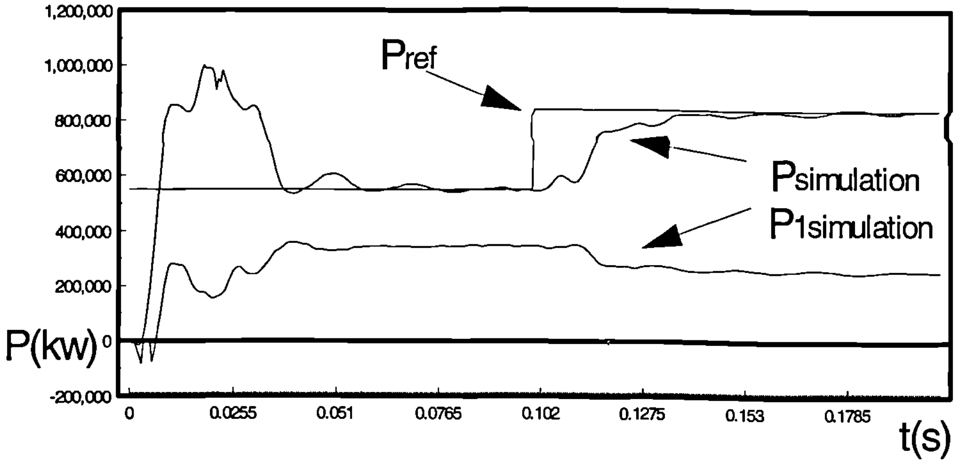


Figure 4-30 (a) The simulation results of the internal controller's performance corresponding to variations of the references

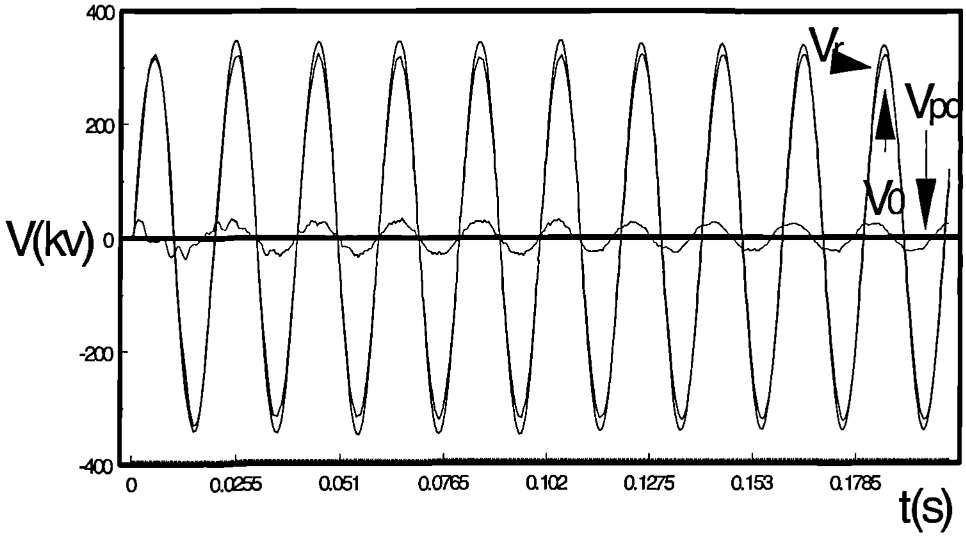


Figure 4-30 (b) The simulation results of the internal controller's performance corresponding to variations of the references

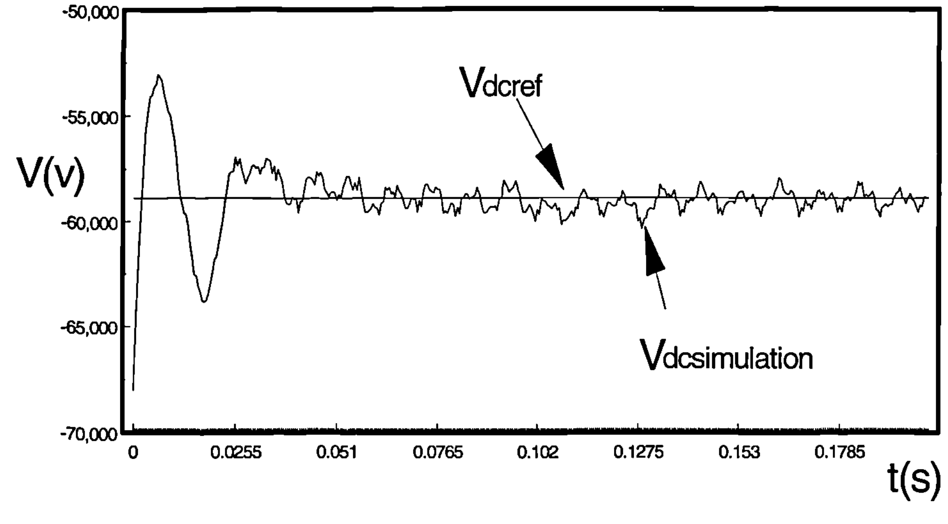


Figure 4-30 (c) The simulation results of the internal controller's performance corresponding to variations of the references

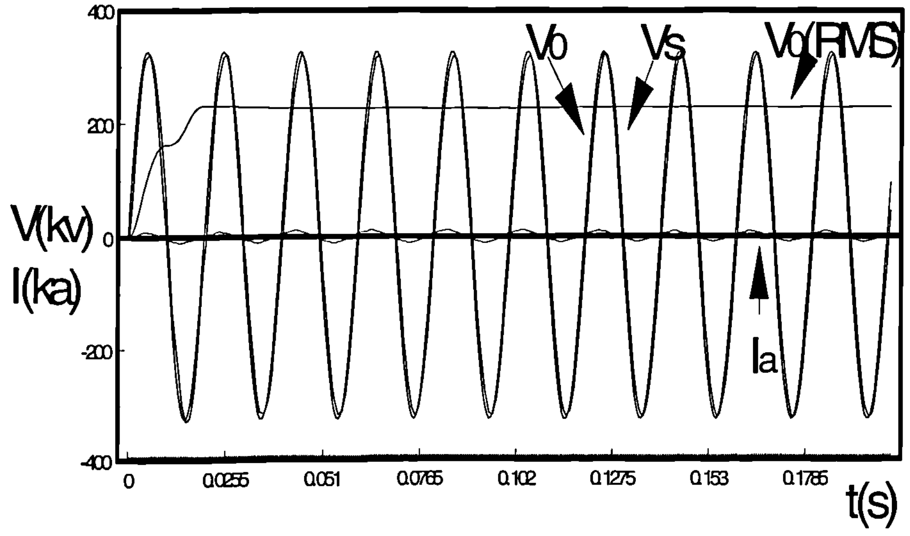


Figure 4-30 (d) The simulation results of the internal controller's performance corresponding to variations of the references

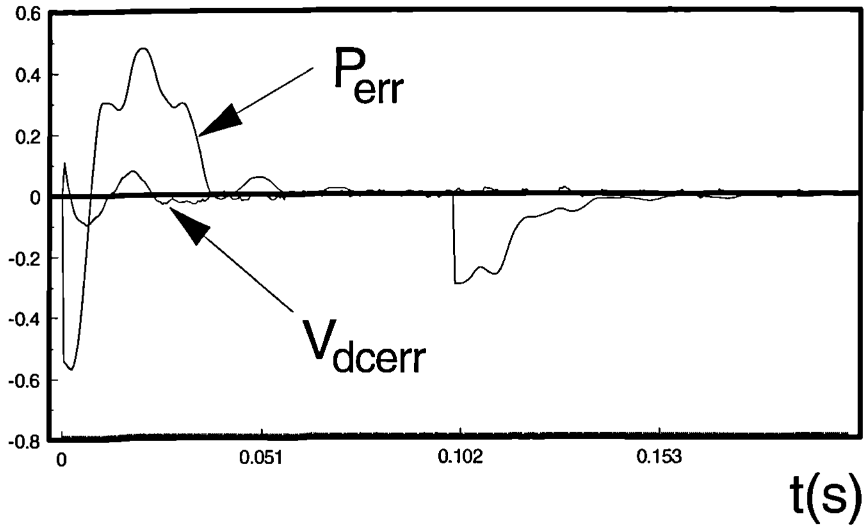


Figure 4-30 (e) The simulation results of the internal controller's performance corresponding to variations of the references

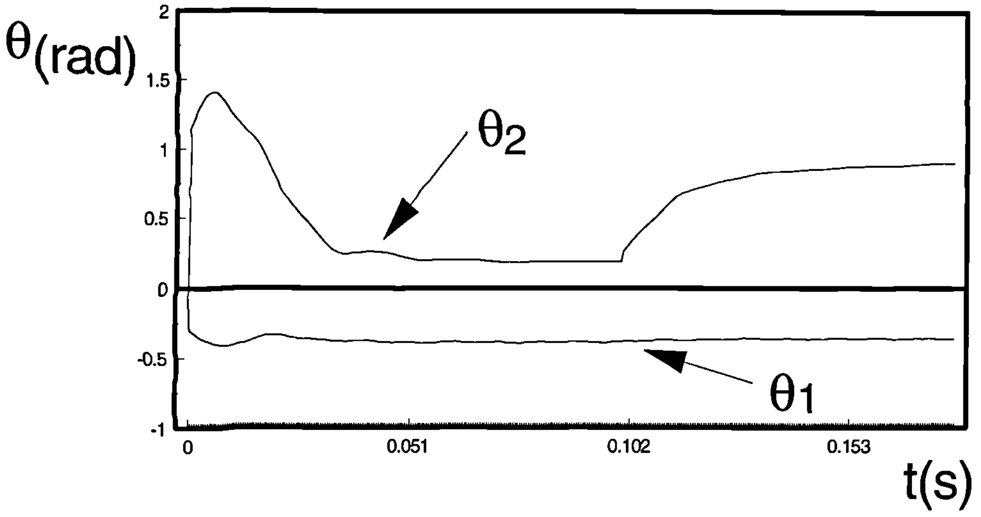


Figure 4-30 (f) The simulation results of the internal controller's performance corresponding to variations of the references

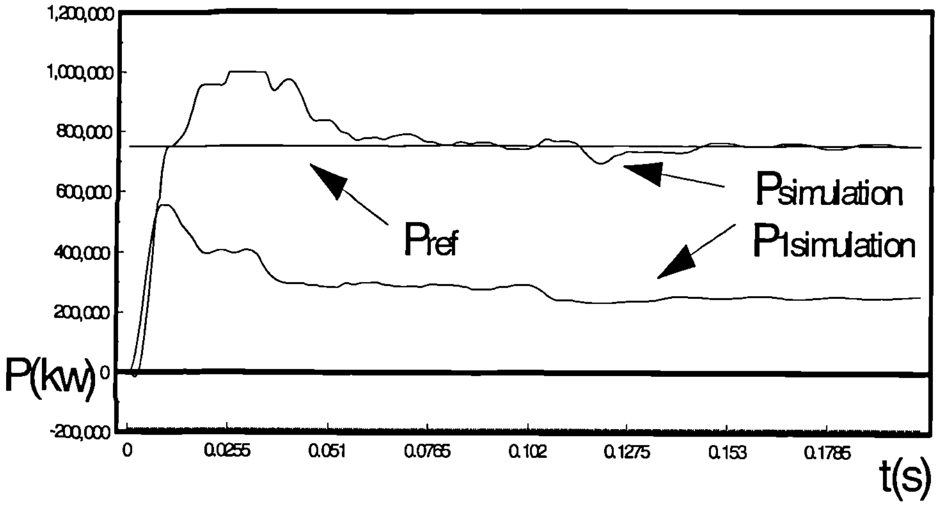


Figure 4-31 (a) The simulation results of the internal controller's performance corresponding to variations of the references

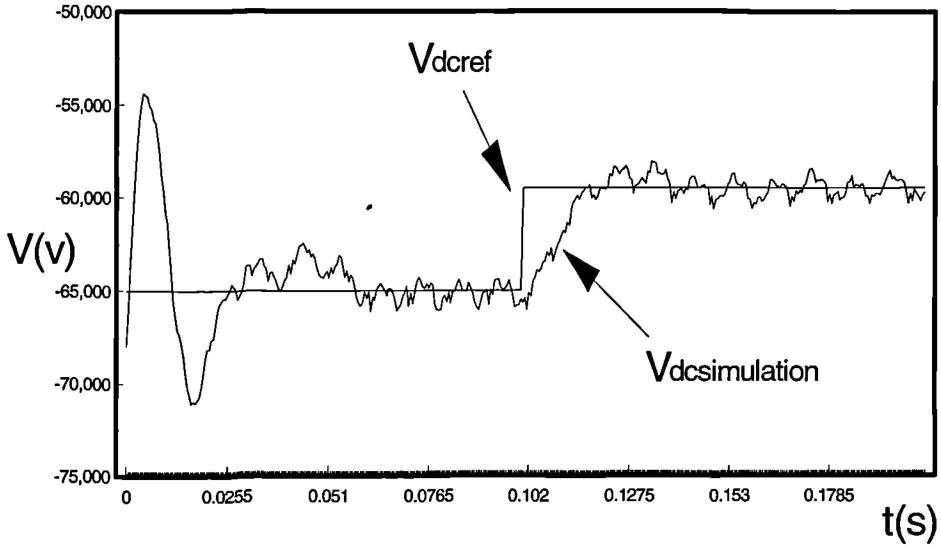


Figure 4-31 (b) The simulation results of the internal controller's performance corresponding to variations of the references

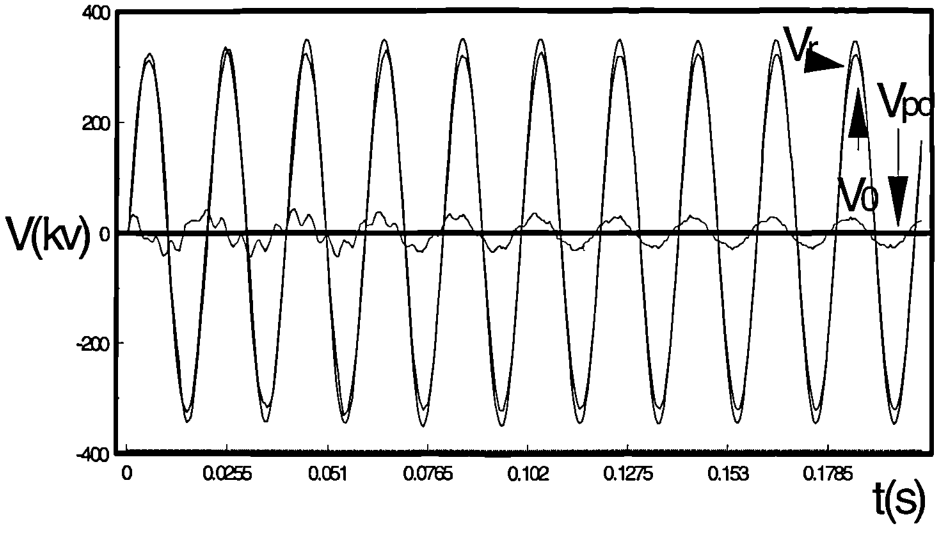


Figure 4-31 (c) The simulation results of the internal controller's performance corresponding to variations of the references

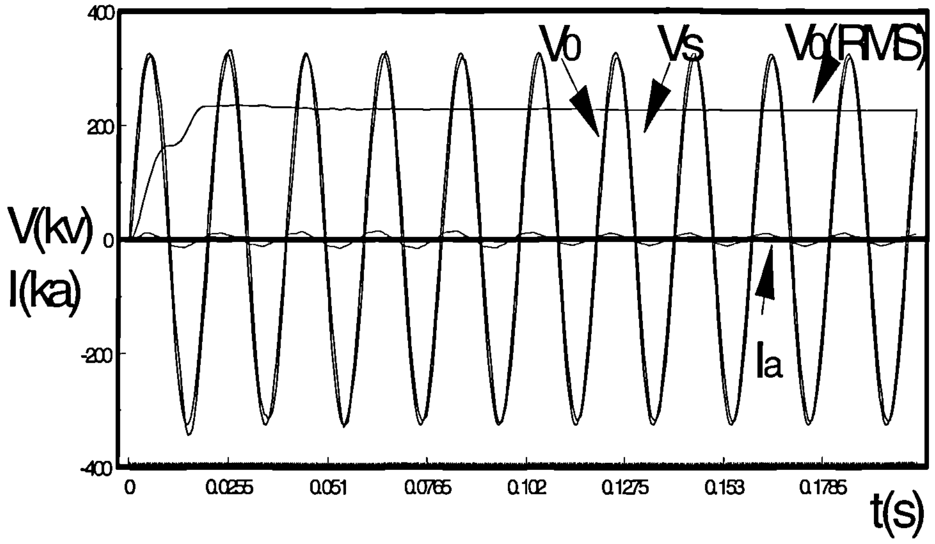


Figure 4-31 (d) The simulation results of the internal controller's performance corresponding to variations of the references

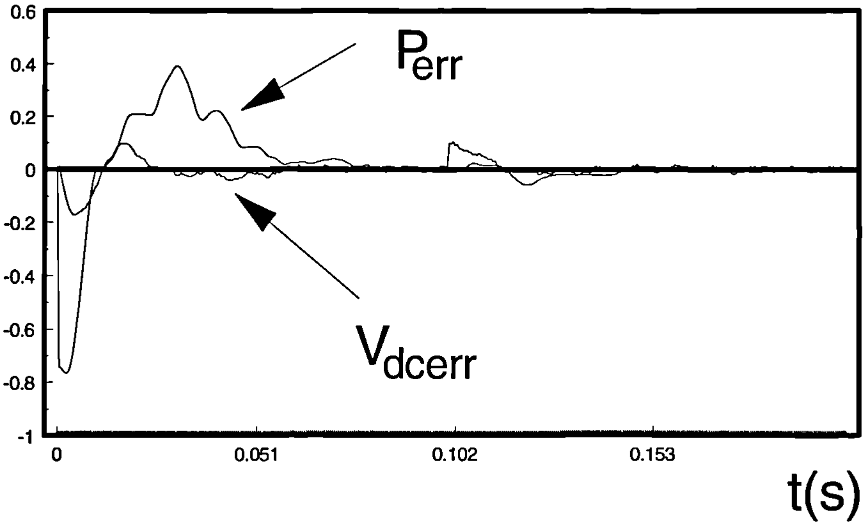


Figure 4-31 (e) The simulation results of the internal controller's performance corresponding to variations of the references

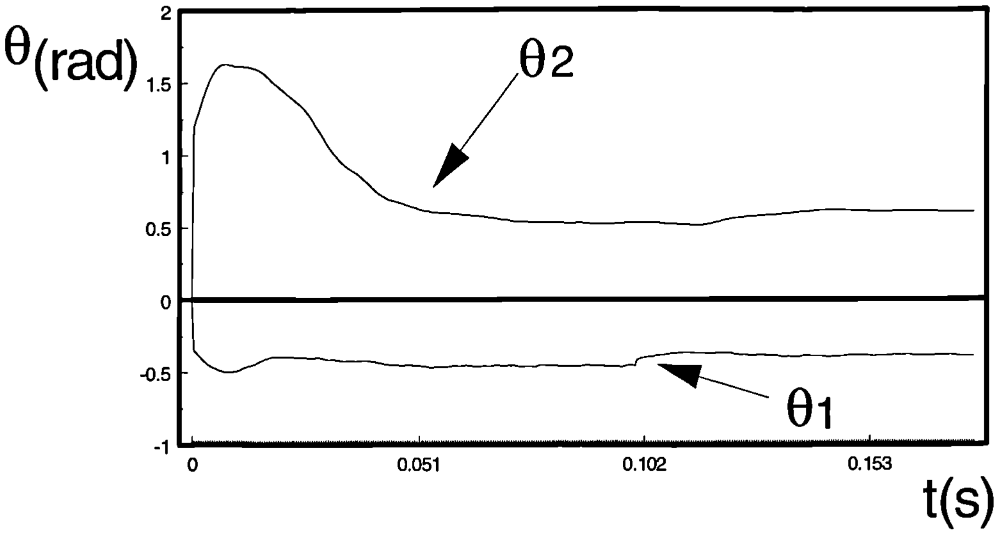


Figure 4-31 (f) The simulation results of the internal controller's performance corresponding to variations of the references

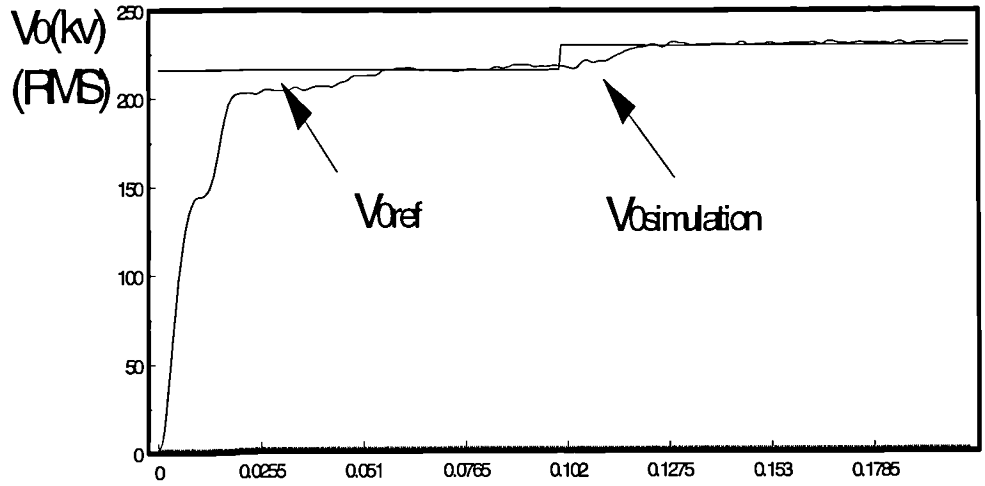


Figure 4-32 (a) The simulation results of the internal controller's performance corresponding to variations of the references

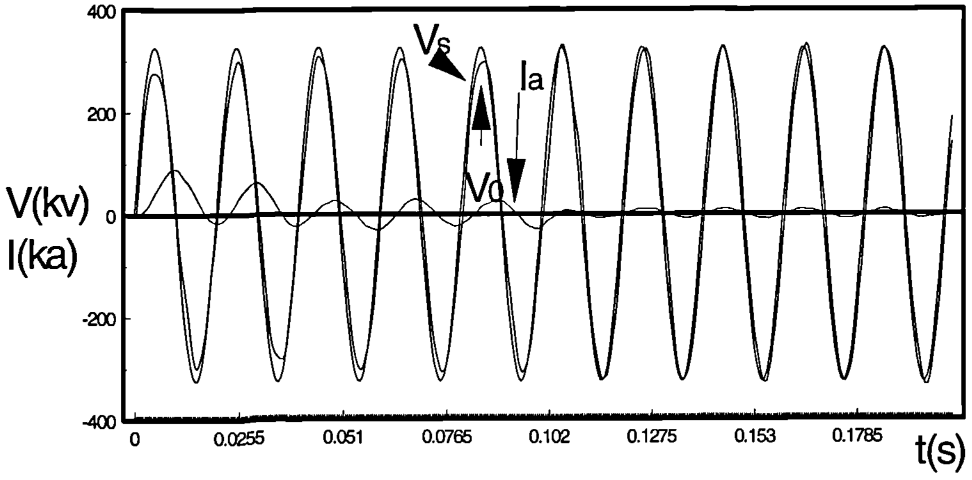


Figure 4-32 (b) The simulation results of the internal controller's performance corresponding to variations of the references

Chapter 5

THE STEADY-STATE UPFC MODELING AND ITS IMPLEMENTATION IN OPTIMAL MULTIPLIER ALGORITHM

5.1 Introduction

In order for the impact of UPFC on power systems to be effectively investigated, its modelling and implementation in power system software are essential. Many of the steady-state models of the UPFC, proposed by [31, 32], treated the UPFC either as one series voltage source and one shunt current source model, or two voltage source model (both the series and the shunt are represented by voltage sources). A generalized power flow controller (GPFC) has also been proposed to represent various power flow control means with a unified mathematical model and a unified data format [128]. These types of the UPFC model were purely derived from concept of the UPFC without considering how these sources representing UPFC models would operate by internal control of the UPFC. Moreover, it is widely recognized [129, 130, 131] that conventional power flow algorithms are convergence failure-prone when applied to power systems with embedded FACTS devices.

The implementation of UPFC models in power flow is essentially a controlled power flow problem. There are two basic ways to handle this problem described in the previous chapter. They are: (i) Error feedback adjustment , which involves modifications of a control variable to maintain another functionally dependent variable at a specified value. (ii) Automatic adjustment, in which the control parameters are directly considered as independent variables so that the resulted Jacobian matrix will be enlarged. Based on the error-feedback adjustment method, Sensitivity-based adjustment has been developed, which is derived from Taylor series expansion of the perturbed system equations around the initial operating point and Distribution factor-based method also has identical structure. Recently, user defined model approach, which has been developed in a number of commercial packages based on the error-feedback method, provides the facilities for users to build their own models.

References [31, 128, 129, 130, 132] used the conventional Newton-Raphson method to implement UPFC steady-state models. Many commercial power system analysis software equipped with user defined model interface have also been employed to evaluate the impacts of the UPFC on various system performances [33, 34, 35]. However, it is difficult or impossible to cover the whole capability range of UPFC in the aforementioned power flow methods. This is largely because of the following two reasons.

On the one hand, this is due to the following peculiarities existing in the UPFC: (i) power transfer between two inverters; (ii) wide regulation range of control parameters; (iii) non-linear multivariable control and (iv) stressed conditions of the system with UPFC. All these make power flow structure very complex and can lead to the increase of iterations or even divergence of power flow [133, 134].

On the other hand [135, 136, 137], this is because: (i) Sensitivity-based adjustment can only work with a very narrow linear range around the initial operating point. (ii) User defined model has no way of dealing with complicated relationship of two inverters of UPFC. The UPFC modelling needs the change of relevant elements of Jacobian matrix. However, the user-defined power flow software do not allow users to directly modify the Jacobian matrix and only provide the facilities for the iteration between the main program and the user defined model. This iteration sometimes diverges, especially when the system is heavily loaded or ill-conditioned. (iii) Although automatic adjustment method has a good convergence, it needs much work to reconstruct Jacobian matrix. Some useful properties such as symmetry and matrix sparsity disappear. It also takes more steps to achieve convergence.

In this chapter, optimal multiplier power flow algorithm [82] will be adopted as it offers a number of advantages in handling ill-conditioned power flow which has been discussed in Chapter 3.

This chapter presents an optimal multiplier based Newton-Raphson power flow algorithm for reliably and efficiently handling power systems with embedded UPFC. The explanation of two voltage sources related with PWM parameters of internal control is given. Furthermore, power injection transformation of two voltage source UPFC model is derived in terms of rectangular form. After detailed analyses of issues in implementation of UPFCs in power flow programmes by various power flow algorithms, the optimal multiplier power flow method for ill-conditioned systems is adopted. The proposed UPFC model and power flow algorithm have been programmed and vigorously tested in a number of systems. The results on the IEEE 30-bus test system and a 306-bus practical system are reported and compared with conventional user defined model type programmes, which clearly illustrate the effectiveness of the proposed algorithm.

5.2 Steady-State UPFC Model for Power Flow Studies

5.2.1 Steady-State UPFC Representation and Its Relations to PWM Parameters

The UPFC consists of two switching inverters, as shown in Figure 5-1 (a), whose operations in equipment level have been discussed in Chapter 4. Studies show that the UPFC can be represented in steady-state by the two voltage sources with appropriate impedances as shown in Figure 5-1 (b). The voltage sources can then be represented by the relationship between the voltages and amplitude modulation ratios, and phase shifts of UPFC, which are links between two operating state models [138, 139, 140]. This means that both voltages representing UPFC model can be expressed in terms of internal control parameters of PWM based on analysis of Chapter 4. Hence, not only voltage source parameters of this model but its internal PWM parameters can be solved through the model associated with power flow computation. The expressions of both voltage sources can be represented by (4-12) and (4-14) in chapter 4. From both equations, it is easy to obtain modulation ratios of both inverters of PWM UPFC once magnitudes of both voltage sources and the dc capacitor voltage are determined. The dc capacitor voltage generally depends on physical rating of the capacitor as well as inverter sizes and arrangement.

However, in order for the model discussed in the thesis to be within range of general purpose steady-state, only parameters of two voltage sources are given without listing associated PWM parameters. The same rule also applies in other chapters without explanation. In this steady-state model, the shunt transformer impedance and the transmission line impedance including the series transformer impedance are assumed to be constant. No power loss is considered within the UPFC. However, the proposed model and algorithm can easily include these when required.

5.2.2 Power Injection Model of UPFC

The two voltage source model of UPFC is converted into two power injections in rectangular form for power flow studies. The advantage of power injection representation is that it does not destroy the symmetric characteristics of admittance matrix [141]. When formulated in rectangular form, the power flow equations are quadratic. Some numerical advantages can be obtained from the form. The rectangular form also naturally leads to the idea of an "optimal multiplier", which has been discussed in Chapter 3.

The following are the formula of the UPFC to be involved in power flow studies.

From Figure 5-2, the first step is to transform the shunt side of UPFC into a power injection at busbar i only. Thus,

$$S_{i0} = P_{i0} + jQ_{i0} = \dot{V}_i \left(\frac{\dot{V}_i - \dot{V}_{sh}}{Z_{i0}} \right)^* \tag{5-1}$$

$$P_{i0} = G_{i0}(V_i^2 - e_i e_{sh} - f_i f_{sh}) + B_{i0}(e_i f_{sh} - f_i e_{sh}) \tag{5-2}$$

$$Q_{i0} = G_{i0}(e_i f_{sh} - f_i e_{sh}) + B_{i0}(e_i e_{sh} + f_i f_{sh} - V_{sh}^2) \tag{5-3}$$

The second step is to convert series source of UPFC into two power injections at both busbars i and j, which is shown in Figure 5-3. Therefore, we have

$$S_i = P_i + jQ_i = \dot{V}_i \left(-\frac{\dot{V}_{pq}}{Z_{ij}} \right)^* \tag{5-4}$$

$$P_i = G_{ij}(-e_i e_{pq} - f_i f_{pq}) + B_{ij}(e_i f_{pq} - f_i e_{pq}) \tag{5-5}$$

$$Q_i = G_{ij}(e_i f_{pq} - f_i e_{pq}) + B_{ij}(e_i e_{pq} + f_i f_{pq}) \tag{5-6}$$

$$S_j = P_j + jQ_j = \dot{V}_j(\frac{\dot{V}_{pq}}{Z_{ij}})^* \tag{5-7}$$

$$P_j = G_{ij}(e_j e_{pq} + f_j f_{pq}) + B_{ij}(f_j e_{pq} - e_j f_{pq}) \tag{5-8}$$

$$Q_j = G_{ij}(f_j e_{pq} - e_j f_{pq}) - B_{ij}(e_j e_{pq} + f_j f_{pq}) \tag{5-9}$$

$$P_{dc} = \mathrm{Re}\left[\dot{V}_{pq}\left(\frac{\dot{V}_i + \dot{V}_{pq} - \dot{V}_j}{Z_{ij}}\right)^*\right]$$

$$= G_{ij}(V_{pq}^2 + e_i e_{pq} - e_j e_{pq} + f_i f_{pq} - f_j f_{pq}) + B_{ij}(e_i f_{pq} - e_j f_{pq} - f_i e_{pq} + f_j e_{pq}) \tag{5-10}$$

where S_{i0} is the power injection of shunt side of the UPFC at the i busbar, P_{dc} is the power transfer from shunt side to series side, S_i and S_j are two power injections transformed from the series voltage at i and j busbars. When power loss inside the UPFC is neglected, i.e $P_{i0}=P_{dc}$, then

$$S_{i(inj)} = S_i - S_{i0} \tag{5-11}$$

$$P_{i(inj)} = G_{ij}(-V_{pq}^2 - 2e_i e_{pq} - 2f_i f_{pq} + e_j e_{pq} + f_j f_{pq}) + B_{ij}(e_j f_{pq} - f_j e_{pq}) \tag{5-12}$$

$$Q_{i(inj)} = G_{ij}(e_i f_{pq} - f_i e_{pq}) + B_{ij}(e_i e_{pq} + f_i f_{pq}) - G_{i0}(-f_i e_{sh} + e_i f_{sh}) + B_{i0}(V_i^2 - e_i e_{sh} - f_i f_{sh}) \tag{5-13}$$

$$S_{j(inj)} = S_j \tag{5-14}$$

$$P_{j(inj)} = G_{ij}(e_j e_{pq} + f_j f_{pq}) + B_{ij}(f_j e_{pq} - e_j f_{pq}) \tag{5-15}$$

$$Q_{j(inj)} = G_{ij}(f_j e_{pq} - e_j f_{pq}) - B_{ij}(e_j e_{pq} + f_j f_{pq}) \tag{5-16}$$

Thus, two power injections($P_{i(inj)}, Q_{i(inj)}$) and($P_{j(inj)}, Q_{j(inj)}$) represent all features of the steady-state UPFC model.

Normally the UPFC control parameters are given in polar form which is more intuitive because the state variables are voltage magnitudes and angles, and have physical meaning. They can be easily transformed from one form to another by the following relationship:

$$V_{pq} = \sqrt{e_{pq}^2 + f_{pq}^2} \tag{5-18}$$

$$\theta_{pq} = \arctan(\frac{f_{pq}}{e_{pq}}) \tag{5-19}$$

$$V_{sh} = \sqrt{e_{sh}^2 + f_{sh}^2} \tag{5-20}$$

$$\theta_{sh} = \arctan(\frac{f_{sh}}{e_{sh}}) \tag{5-21}$$

5.3 Representation of UPFC for Power Flow

5.3.1 Optimal Multiplier Power Flow Algorithm

Consider the power flow equations for an N busbar system:

$$S = F(X) \tag{5-22}$$

where S is a vector of the power injections at all buses except the slack bus.

$$S = [P_1,\dots, P_M , P_{M+1},\dots, P_{N-1}, Q_1,\dots, Q_M ,V_{M+1}^2,\dots,V_{N-1}^2] \tag{5-23}$$

where M represents the number of PQ bus, N-M-1 is the number of PV bus.

When x is expressed using rectangular coordinates of bus voltages, we have

$$X = [e_1,\dots,e_{N-1},f_1,\dots,f_{N-1}] \qquad (5\text{-}24)$$

and f is the function of the bus power balance constraints.

$$F = [f_{p1},\dots,f_{pN-1},f_{q1},\dots,f_{qM},f_{qM+1},\dots,f_{qN-1}] \qquad (5\text{-}25)$$

The *t*th iteration of the power flow solves the equations:

$$\Delta X^t = -J(X^t)^{-1}[F(X^t)-S] \qquad (5\text{-}26)$$

$$X^{t+1} = X^t + \mu\Delta X^t \qquad (5\text{-}27)$$

where $J(X^t)$ is the Jacobian matrix at the *t*th iteration.

The μ in equation (5-27) is a scalar multiplier used to control the updating of variables at each iteration. In the traditional Newton-Raphson algorithm, $\mu=1$ at each iteration. With Optimal Multiplier Power flow Algorithm, a scalar 'optimal multiplier' μ is chosen to minimize a cost function, shown as equation (5-28), in the direction given by ΔX^t so that the updates of variables at each iteration converge in a optimal way to the solution point. In this respect, the cost function is set to equal to one half the norm of the power flow mismatch equations:

$$Goal(X^{t+1}) = \frac{1}{2}[f(X^t+\mu\Delta X^t)-S]^T[f(X^t+\mu\Delta X^t)-S] \qquad (5\text{-}28)$$

Then μ is determined by the following steps:

Let

$$a = [a_1,\dots,a_N]^T = S - F[X_t] \qquad (5\text{-}29)$$

$$b = [b_1,\ldots,b_N]^T = -J\Delta X \tag{5-30}$$

$$c = [c_1,\ldots,c_N]^T = -F(\Delta X) \tag{5-31}$$

Then the equation (5-28) becomes:

$$Goal = \frac{1}{2}\sum_{i=1}^{N}(a_i + \mu b_i + \mu^2 c_i)^2 = Goal(\mu) \tag{5-32}$$

In order to solve the minimal value of the objective function Goal, one solves:

$$\frac{dGoal}{d\mu} = 0 \tag{5-33}$$

Therefore,

$$g_0 + g_1\mu + g_2\mu^2 + g_3\mu^3 = 0 \tag{5-34}$$

where

$$\begin{cases} g_0 = \sum_{i=1}^{N}(a_i b_i) \\ g_1 = \sum_{i=1}^{N}(b_i^2 + 2a_i c_i) \\ g_2 = 3\sum_{i=1}^{N}(b_i c_i) \\ g_3 = 2\sum_{i=1}^{N} c_i^2 \end{cases} \tag{5-35}$$

Thus the equation (5-34) can be solved easily by the Cardan's formula analytically or Newton method numerically.

5.3.2 UPFC Modified Jacobian Matrix Elements

In power flow, the two power injections($P_{i(inj)}, Q_{i(inj)}$) and ($P_{j(inj)}, Q_{j(inj)}$) of a UPFC can be treated as generators. However, because they vary with the connected busbar voltage amplitudes and phases, the relevant elements of the Jacobian matrix will be modified at each iteration. The formation of Jacobian matrix is $J = \begin{bmatrix} H\,N \\ M\,L \end{bmatrix}$ for PQ bus. Based on the equations (5-12), (5-13) and (5-15) and (5-16), the following additional elements of Jacobian matrix owing to the injections of the UPFC at the i and j busbars can be derived :

for i busbar, $i \neq j$ then

$$\Delta H_{ij} = \frac{\partial P_{i(inj)}}{\partial f_j} = G_{ij} f_{pq} - B_{ij} e_{pq} \tag{5-36}$$

$$\Delta N_{ij} = \frac{\partial P_{i(inj)}}{\partial e_j} = G_{ij} e_{pq} + B_{ij} f_{pq} \tag{5-37}$$

$$\Delta M_{ij} = \frac{\partial Q_{i(inj)}}{\partial f_j} = 0 \tag{5-38}$$

$$\Delta L_{ij} = \frac{\partial Q_{i(inj)}}{\partial e_j} = 0 \tag{5-39}$$

when i=j

$$\Delta H_{ii} = \frac{\partial P_{i(inj)}}{\partial f_i} = -2\, G_{ij} f_{pq} \tag{5-40}$$

$$\Delta N_{ii} = \frac{\partial P_{i(inj)}}{\partial e_i} = -2\, G_{ij} e_{pq} \tag{5-41}$$

$$\Delta M_{ii} = \frac{\partial Q_{i(inj)}}{\partial f_i} = -G_{ij} e_{pq} + B_{ij} f_{pq} + G_{i0} e_{sh} + 2B_{i0} f_i - B_{i0} f_{sh} \qquad (5\text{-}42)$$

$$\Delta L_{ii} = \frac{\partial Q_{i(inj)}}{\partial e_i} = G_{ij} f_{pq} + B_{ij} e_{pq} - G_{i0} f_{sh} + 2B_{i0} e_i - B_{i0} e_{sh} \qquad (5\text{-}43)$$

for j busbar, $j \neq i$

$$\Delta H_{ji} = \frac{\partial P_{j(inj)}}{\partial f_i} = 0 \qquad (5\text{-}44)$$

$$\Delta N_{ji} = \frac{\partial P_{j(inj)}}{\partial e_i} = 0 \qquad (5\text{-}45)$$

$$\Delta M_{ji} = \frac{\partial Q_{j(inj)}}{\partial f_i} = 0 \qquad (5\text{-}46)$$

$$\Delta L_{ji} = \frac{\partial Q_{j(inj)}}{\partial e_i} = 0 \qquad (5\text{-}47)$$

when j=i

$$\Delta H_{jj} = \frac{\partial P_{j(inj)}}{\partial f_j} = G_{ij} f_{pq} + B_{ij} e_{pq} \qquad (5\text{-}48)$$

$$\Delta N_{jj} = \frac{\partial P_{j(inj)}}{\partial e_j} = G_{ij} e_{pq} - B_{ij} f_{pq} \qquad (5\text{-}49)$$

$$\Delta M_{jj} = \frac{\partial Q_{j(inj)}}{\partial f_j} = G_{ij} e_{pq} - B_{ij} f_{pq} \qquad (5\text{-}50)$$

$$\Delta L_{jj} = \frac{\partial Q_{j(inj)}}{\partial e_j} = -G_{ij} f_{pq} - B_{ij} e_{pq} \tag{5-51}$$

5.3.3 Normal (Open-Loop) and Controlled (Close-Loop) Power Flow With UPFC

There are two aspects when handling the UPFC in steady state analysis: (i) When the control parameters of UPFC are given (i.e. e_{sh} f_{sh} e_{pq} f_{pq} are given), power flow programme is used to evaluate the impact of the given UPFC on the system under various system conditions. In this case, UPFC is operated in an open-loop form. The corresponding power flow is treated as normal power flow. This is the topic of this chapter. (ii) As UPFC can be used to control line flow and bus voltage, control techniques are needed to derive the UPFC control parameters to achieve the required objective. In this case, the UPFC is operated in a close loop form. The corresponding power flow is called controlled power flow. It will be discussed in some details in Chapters 7 and 8.

5.4 Implementation of UPFC in Power Flow Studies

5.4.1 Power Flow Procedure with UPFC

The overall procedures of the proposed algorithm can be summarised as:

Step 1: Input data needed by conventional power flow; Order Busbar optimally; Form admittance matrix; Input UPFC series and shunt voltage amplitudes and phases (which can be derived by control strategies as described in the late chapter);

Step 2: Form conventional Jacobian matrix; Modify the Jacobian matrix using UPFC injection elements to become the enhanced Jacobian matrix according to the equations (5-36) - (5-51);

Step 3: Use the enhanced Jacobian matrix to solve busbar voltage until the convergence of all power injections is achieved. In this step, the optimal multiplier μ is calculated using Newton method. When the mismatch at every busbar is less than prescribed error, the power flow converges. Otherwise go to Step 2;

Step 4: Output system voltages and line flows; Display various information about the UPFC.

5.4.2 Conventional User Defined Model with UPFC

Many commercial power system analysis software provide users with user defined model to model FACTS and other control equipment. However, the user can only change the interactions of the main programs and user defined models and cannot modify the Jacobian matrix owing to the executive and unmodified main program provided by the software. In order to compare the results of the proposed method (PM) and user defined model (UDM), both methods are programmed.

5.5 Test Results

In order to investigate the feasibility of the proposed technique, a large number of power systems of different sizes and under different system conditions have been tested. All the results indicate good convergence and high accuracy achieved by the proposed method. In this section, the IEEE 30-bus system and a 306-bus practical system have been presented to numerically demonstrate its performance.

5.5.1 IEEE 30-Bus System

The performances of UPFC on the IEEE 30-bus system shown in Figure 5-4 are first evaluated by nine operating conditions, which are shown in Table 5-1. In all cases, the following assumption has been made: Z_{i0}=0.0+j0.02, and Z_{ij}=0.0+j0.002.

A large number of cases have been conducted, which clearly illustrate the effectiveness and fast convergence of the proposed method. Figures 5-5, 5-6 and 5- 7 are examples of the convergence comparison between PM and UDM on the IEEE-30 system. These diagrams show the relationships between optimal multiplier μ, cost function (Goal) and iteration numbers. Figures5-5(a) and 5-5(b) present the cases in which both methods converge but with different speed and errors. PM converges at 5 iterations while UDM converges at 9 iterations with both m and Goal equal to zero. With the increase of the control parameter V_{pq} from 0.1 to 0.13, PM converges fast but UDM diverges. This is shown in Figures 5-6(a) and 5-6(b). Furthermore, when V_{pq}=0.4, PM diverges at 17 iterations with m zero as shown in Figures 5-7. At this point, Goal remains 11.593 which is minimum value during iterations. All these figures, in which V_6 keeps 1.03 p.u., show that the proposed method converges faster and more reliably.

5.5.2 306-Bus Practical System

The second system which is a practical system consists of 306 buses, 521 lines, 38 generators, 147 transformers (including 35 on-line tape changer) and 171 load buses. The total generation is 11000.0 MW. The system is divided into seven areas. The aim of four UPFC installations in the main voltage sensitive points and the associated transmission lines is to balance power transmissions and improve voltage profile. Many operating conditions have been investigated to achieve the optimal operation of the system with UPFCs. Table 5-2 is one of the results with specified UPFC parameters compared with the power flow results without UPFC. Figures 5-8 and 5-9 show the μ and the real power mismatch with four UPFCs. The program converges at 4 iterations.

5.6 Summary

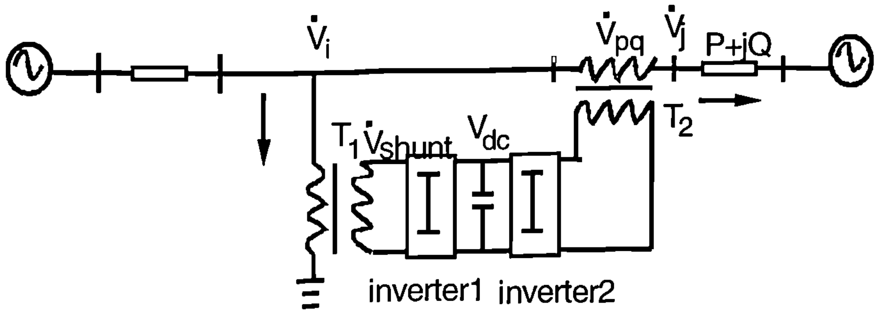
This chapter reports on the development of steady-state UPFC model and its implementation into a power flow algorithm. A steady-state UPFC model has been proposed and explained with relations to PWM parameters of internal control and furthermore its power injection transformation has been derived in rectangular form. The optimal multiplier power flow method for ill-conditioned system has been employed to implement the UPFC model. The proposed UPFC model and power flow algorithm, compared with user defined model, have been vigorously tested in a number of systems. The results on the IEEE 30-bus test system and a 306-bus practical system clearly illustrate the effectiveness of the proposed algorithm. The studies of the proposed power injection model technique with embedded UPFC for power flow control and voltage support will be reported in the late chapter.

Table 5-1 Operating conditions

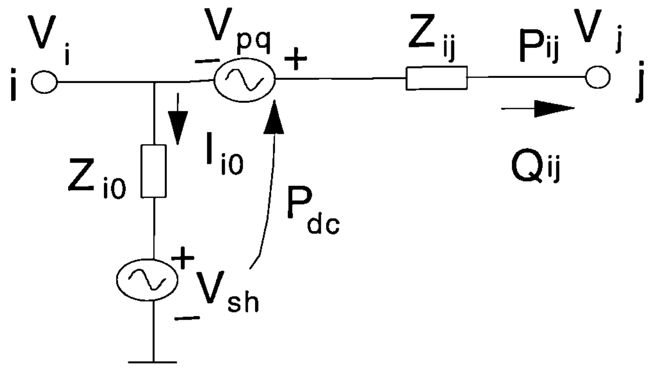
case	capacitor of bus 10	line 6-28	i and j bus with UPFC	V_{sh}	V_{pq}
1 (base case)	on	on	none	none	none
2 (outage 1)	off	on	none	none	none
3	off	on	10 - 22	$1.05\angle -10.3^0$	$0.1\angle 0.0^0$
4	off	on	10 - 22	$1.049\angle -10.4^0$	$0.1\angle 90.0^0$
5 (outage 2)	on	off	none	none	none
6	on	off	6 - 8	$1.071\angle -6.9^0$	$0.1\angle 0.0^0$
7	on	off	6 - 8	$1.042\angle -13.6^0$	$0.1\angle 90.0^0$
8	on	off	6 - 8	$1.096\angle -7.1^0$	$0.1\angle 0.0^0$
9	on	off	6 - 8	$1.170\angle -9.84^0$	$0.3\angle 0.0^0$

Table 5-2 Comparison between power flow results with and without UPFCs

UPFC location and parameters	11-23: $V_{pq}=0.032\angle 90.0^0$ $V_{sh}=0.974\angle -4.21^0$ 36-54: $V_{pq}=0.02\angle 45^0$ $V_{sh}=0.99\angle 3.8^0$ 60-62: $V_{pq}=0.015\angle 180^0$ $V_{sh}=1.00\angle 3.2^0$ 67-68: $V_{pq}=0.01\angle 235.0^0$ $V_{sh}=1.012\angle 7.2^0$			
power flows without UPFC	$V_{11}=1.0215$ $P_{11-23}=0.8448$	$V_{36}=0.96302$ $P_{36-54}=-2.1519$	$V_{60}=1.03336$ $P_{60-62}=-0.2902$	$V_{67}=1.05197$ $P_{67-68}=-0.4897$
power flows with UPFCs	$V_{11}=1.000$ $P_{11-23}=-7.0819$	$V_{36}=0.9800$ $P_{36-54}=-2.3015$	$V_{60}=1.010$ $P_{60-62}=-0.2960$	$V_{67}=1.020$ $P_{67-68}=-0.1296$



(a) UPFC structure



(b) Two voltage source model

Figure 5-1 The UPFC structure and its two voltage source model

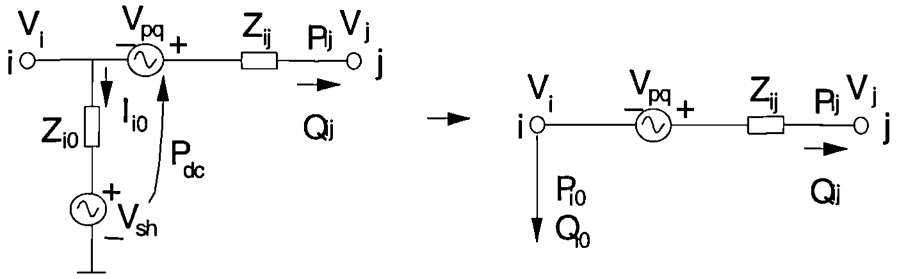


Figure 5-2 The shunt side of UPFC is converted into power injection at busbar i only

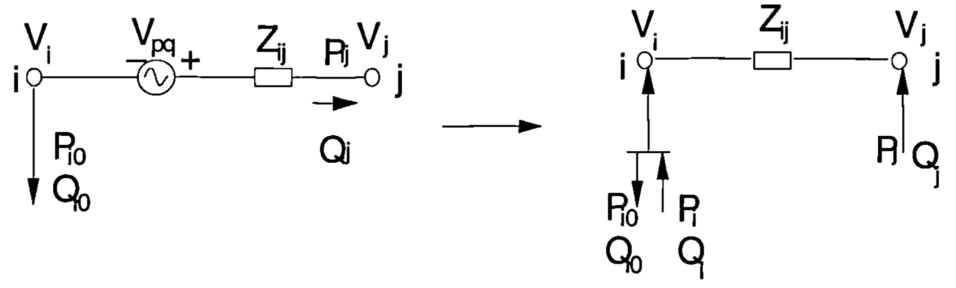


Figure 5-3 The series side of UPFC is converted into two power injections at buses i and j

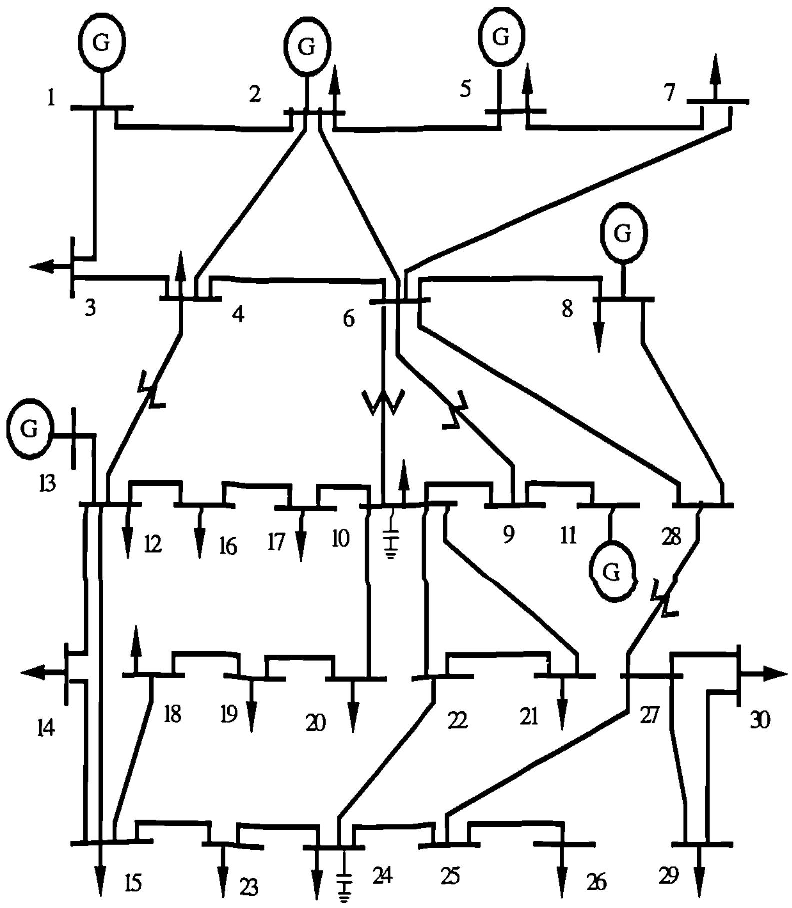


Figure 5-4 IEEE 30-bus system

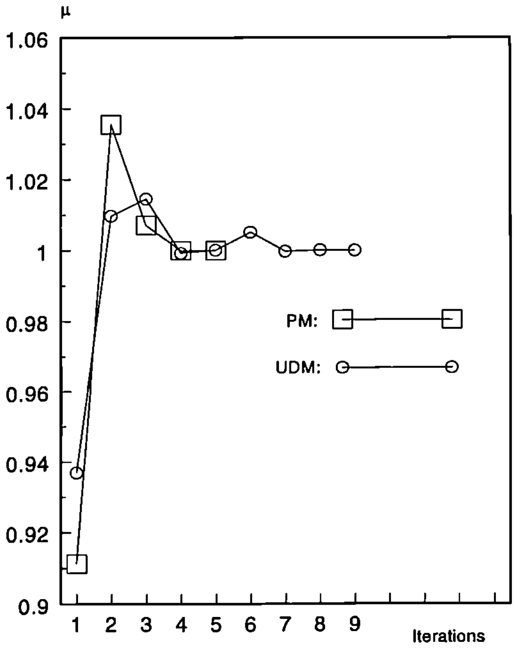


Figure 5-5(a) Optimal multiplier μ vs. iteration number under case 7 with $V_{pq}=0.1\angle 90.0^0$

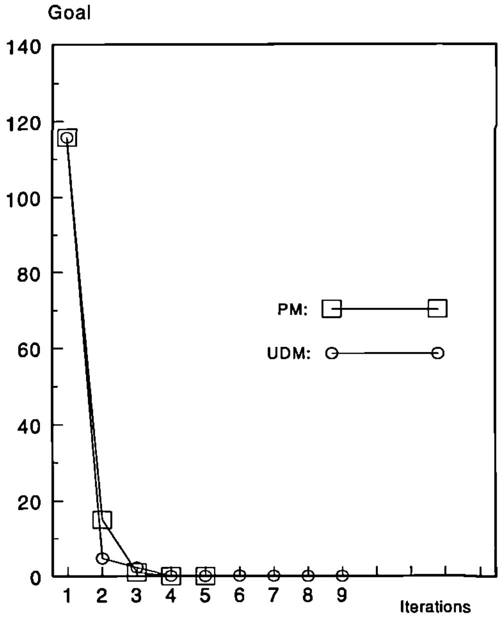


Figure 5-5(b) Goal vs. iteration number under case 7 with $V_{pq}=0.1\angle 90.0^0$

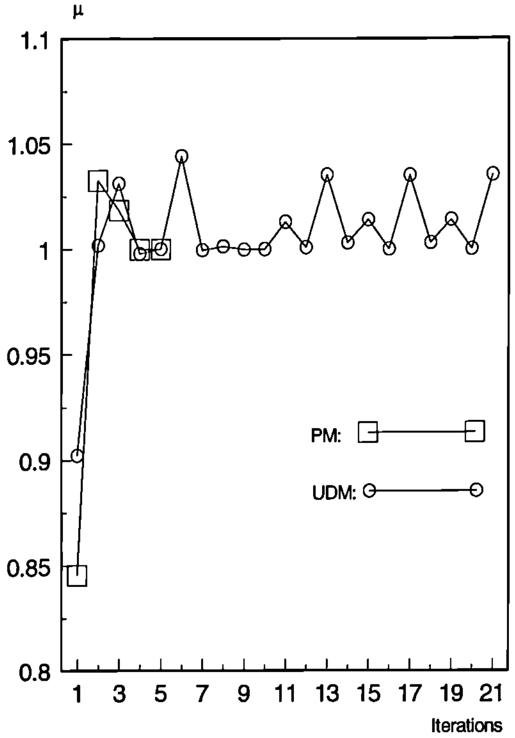


Figure 5-6(a) Optimal multiplier μ vs. iteration number under case 7 with $V_{pq}=0.13\angle 90.0^0$

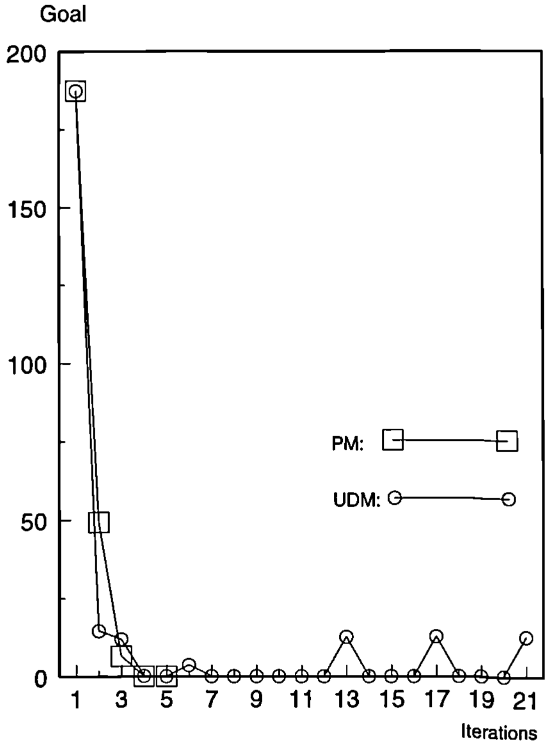


Figure 5-6(b) Goal vs. iteration number under case 7 with $V_{pq}=0.13\angle 90.0^0$

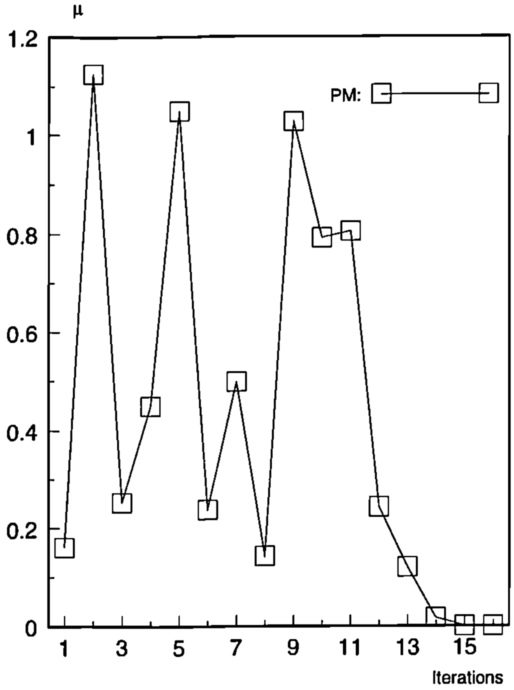


Figure 5-7(a) Optimal multiplier μ vs. iteration number under case 7 with $V_{pq}=0.4\angle 90.0^0$

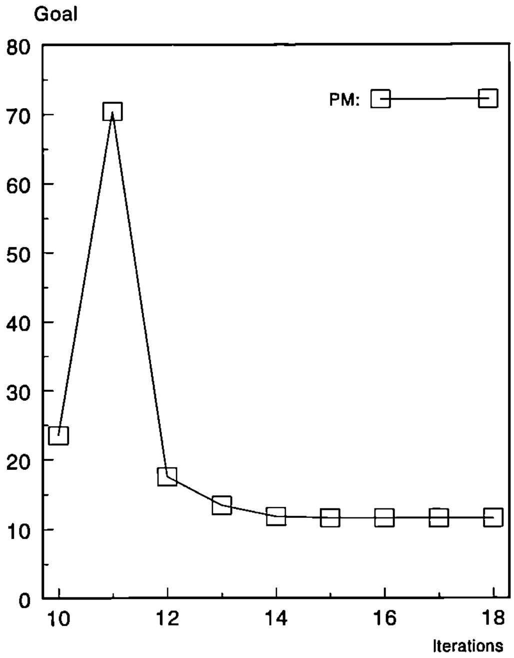


Figure 5-7 (b) Goal vs. iteration number under case 7 with $V_{pq}=0.4\angle 90.0^0$

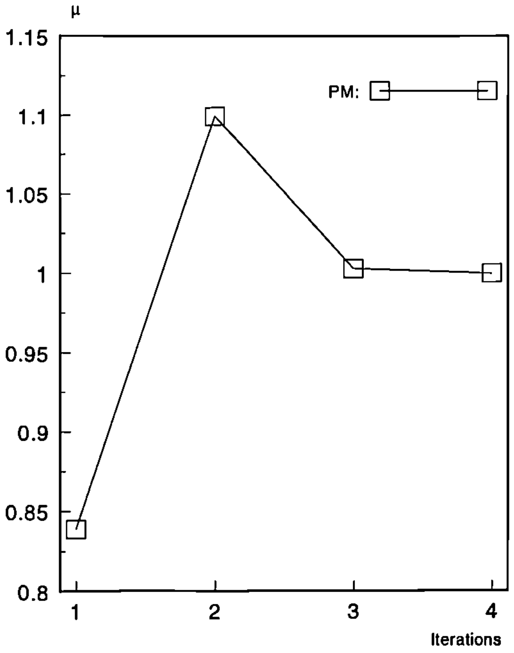


Figure 5-8 Optimal multiplier μ vs. iteration number

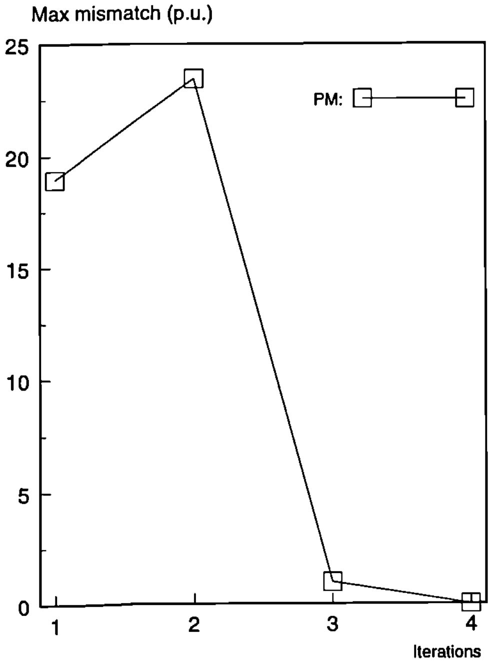


Figure 5-9 Maximum mismatch vs. iteration number

Chapter 6

DETERMINING MAXIMUM REGULATING CAPABILITY OF UPFC BASED ON PREDICTING FEASIBILITY LIMIT OF POWER SYSTEMS

6.1 Introduction

Since power systems have being operated under more stressed conditions, a number of controllable devices have been employed for the reinforcement of transmission networks. UPFC has been under heavy investigation since it has been proposed. In this respect, its impacts on the performance of the system or vice versa should be evaluated.

Two references [33, 36] have investigated the performance of UPFC with injected current limits for the shunt inverters, power transfer limits between inverters, voltage injection limits for the series inverters, current limits for the series inverters, and line voltage limits for the transmission line. In paper [38], scalar measures of the steady-state performance of a power system with FACTS devices have been obtained by solving optimal power flow within the constraints of security region, which demonstrated that the capabilities of UPFC can be represented by two independent complex current sources. However, one important question still needs to be addressed, i.e., how much can the controllable parameters of the UPFC be regulated to push the system to achieve the boundary of feasibility region of steady-state power flow solution? The question is raised because it is possible to have cases where a feasibility limit is reached before a thermal limit or other steady-state security limits [142]. Therefore, answers to this question can give operators and planners information about the controllable size and rating of UPFC, and system critical points. The difficulty of estimating boundary points of feasibility region lies in locating the boundary points at which the conventional power flow Jacobian matrix becomes singular.

This chapter is organized as follows. The concept of feasibility region constrained by FACTS control parameters is introduced from the concept of the steady-state power system feasibility region. Then, optimal multiplier algorithm is chosen to incorporate the UPFC model. A step-by-step procedure of determining the maximum regulating capability of the UPFC is proposed based on the predicted boundary point of the feasible region. The studies of the IEEE-30 bus system have been compared with minimum singular value decomposition method. The regulating capabilities of the UPFC under different parameter patterns are presented.

6.2 Concept of Control Parameter Regulating Capability of FACTS Equipment

6.2.1 Concept of Feasibility

Generally speaking, power flow feasibility is concerned with those conditions on the parameters characterizing the network and its bus injections, under which a steady-state equilibrium exists. Mathematically, the feasibility property is a consequence of the fact that the power flow equations have a real solution only for certain combinations of the network parameters and injections. From the physical point of view, feasibility is a consequence of the law of conservation of energy. Practically, feasibility imposes constraints on the network variables and parameters which the planner and operator must take into account together with all other security constraints. The boundary theorem of feasibility region is that the Jacobian matrix of power flow corresponding to the boundary injection is singular. So, seeking the boundary point of feasibility region is to find the feasibility limit associated with singularity of the conventional power flow Jacobian matrix.

6.2.2 Relationship Between FACTS Feasibility Regions and The Control Parameter Regulating Capabilities

It is found that the power system may collapse owing to the major change of control parameters. The mechanism of collapse of network with the increasing of control parameters is similar to that of voltage instability, but they have different meanings. Feasibility region of voltage stability means the boundary of maximum loads under which the system can endure without voltage collapse, and feasibility region of control parameters of FACTS devices describes the maximum values of control parameters which do not result in collapse of the system. Compared to the operational limits and security region of FACTS devices, the feasibility region is important to understand the impacts of control parameters on the system performance and is the foundation to determine maximum control values during operation. Thus, it can be further used to design the ratings and sizes of FACTS devices during planning. However, since many FACTS devices such as the UPFC have several control parameters to be defined, their global feasibility regions are of hyperspace and are not easy to be formed and demonstrated. Thus the general method is to constantly change one of the control parameters until the system reaches the collapse point of the feasibility region while others are fixed. In this case, the value of the system state variable of interest corresponding to the control parameter represents the maximum regulating capability based on feasibility limit.

Although many methods [143, 144, 145, 146, 147, 148, 149] developed so far are concerned with the exact computations of feasibility regions or critical points of voltage stability, they all need much more additional computation efforts in addition to conventional power flow calculation and also is not suitable for our studies. Therefore, there is a need to develop a new method of quickly and exactly predicting collapse points of feasibility regions so as to define the regulating capability of the UPFC.

6.3 New Approach to Predict the Collapse Point of the Feasibility Region and to Compute the Maximum Regulating Capability of UPFC

In this section, optimal multiplier power flow method is introduced as a tool, in which the use of optimal multiplier μ as a predictor to estimate the boundary point is explained. The optimal multiplier method incorporated with UPFC model and the procedure to compute the maximum regulating capability of UPFC are presented at last.

6.3.1 Optimal Multiplier μ as A Predictor

Optimal multiplier power flow algorithm is used in the UPFC studies because it offers a number of advantages in handling ill-conditioned power flow, which has been already described in detail in Chapter 5. Here we only explain why the optimal multiplier can be used as a predictor of detecting singularity of Jacobian matrix.

When optimal multiplier algorithm is used to calculate power flow, the optimal multiplier μ generally tends to behave in two ways:

(i) μ is around one.

(ii) μ tends to be zero.

For the first case, the solution of power flow converges, while the second case is corresponding to divergence of power flow solution. The reason is as follows:

If the solution of power flow converges, it should satisfy:

$$X^{t+1} \cong X^{t} \qquad (6\text{-}1)$$

From the equation $X^{t+1} = X^{t} + \mu \Delta X^{t}$, we know that if equation (6-1) is satisfied and μ is around one, there should be:

$$\Delta X^{t} \rightarrow 0 \qquad (6\text{-}2)$$

Obviously, this is a convergence condition of power flow and thus X^{t+1} is the solution of power flow. However, if equation (6-1) is also satisfied but μ tends to zero, ΔX^{t} is liable to diverge. In this case, Jacobian matrix $J(X^{t})$ in $\Delta X^{t} = -J(X^{t})^{-1}[F(X^{t}) - S]$ will be singular. Therefore, the conclusion can be made that the fact that the optimal multiplier μ tends to be zero is corresponding to the singularity of Jacobian matrix in optimal multiplier power flow method. It is because of this characteristics of μ that we choose it as the indictor to predict the boundary points of feasibility regions when the UPFC control parameters change.

As it is pointed out that in all existing methods of finding voltage collapse point of voltage instability much more additional computations are unavoidable in addition to power flow computations. Here, it is easy to obtain the collapse point without any additional computation by only using optimal multiplier μ as the predictor because the μ can be obtained during the iterations of power flow calculation.

6.3.2 Procedure of Predicting the Boundary Point and Forming Maximum Regulating Capability of UPFC

The details of optimal multiplier algorithm implemented with this UPFC model have been investigated in Chapter 5. Based on the predictor μ and the steady-state UPFC model incorporated in optimal multiplier power flow method, a new algorithm to predict the boundary point and form the maximum regulating capability of UPFC is developed:

(1) Prepare system data and network structure for conventional power flow calculations; Select one or two variables by operators to represent the capability regulated by UPFC parameters of interest; Set a flat start of power flow; It should be noticed that in this algorithm the Jacobian matrix elements are taken into account of UPFC parameters.

(2) Determine the regulating range and direction of control parameter space of UPFC; Set up an initial point of control parameters;

(3) Run the optimal multiplier power flow; Check three conditions:

(i) If $\mu=1.0$ and the mismatch of power flow is satisfied, power system converges and go to (4);

(ii) If $\mu=0$, power system diverges and record the control parameters and state variables which is the boundary point of this control parameter; then go to (5);

(iii) If μ is neither 1.0 nor zero but tends to decreasing, then increasing control parameters and repeat (3);

(4) Increase the control values but fix direction of parameters, repeat (3) until reach the range of control parameters limit; go to the final step (6);

(5) Change the direction of control parameters and fix a new initial point of control parameter, go to (3);

(6) Use the variables obtained from every collapse point of control parameters to form the maximum regulating capability.

In order to prove optimal multiplier μ as a predictor to estimate the collapse point caused by the change of UPFC parameters, SVD is employed to compare the results obtained by the proposed method. With the use of SVD, the whole Jacobian matrix of power flow is involved.

6.4 Test Results on IEEE 30-Bus System

In order to numerically test the proposed technique on UPFC control parameters, the IEEE 30-bus system is employed. The performances of UPFC are evaluated by the many operating conditions. In the studies, the following assumption has been made: Z_{i0}=0.0+j0.01, and Z_{ij}=0.0+j0.01.

6.4.1 Data Preparation

In order to evaluate the feasibility region of UPFC parameters, Three steps should proceed in advance:

(1) Prepare system data and structure;

(2) Analyze contingency and determine the installation location of UPFC in the network;

(3) Determine the range limit and change direction of UPFC control parameters.

Here the first two steps are briefly described as they are out the scope of the chapter. The outage occurs on transmission line 6 - 28 which results in the violation of transmission line 6 - 8 transfer power against thermal limit and also forces the voltage of bus 6 to fall below the lower limit (0.95p.u.). Thus a UPFC is installed in line 6--8, whose shunt part is connected at bus 6. Its functions of controlling voltage of bus 6 and regulating transfer power of line 6 - 8 have been demonstrated in our studies. The final step to determine the range and direction of UPFC should follow the regulation law of UPFC. Therefore, we have the range space S of UPFC parameters:

$$S = \{UPFC / \|V_{pq}\| \leq 1.0, \|V_{shunt}\| \leq 1.0, 0 \leq \theta_{pq}, \theta_{shunt} \leq 360^0\} \tag{6-3}$$

However, when applying the UPFC in the system, it is required that the shunt part of UPFC should control the connected bus voltage which means the controlled bus voltage is within the limit of voltage profile. Thus the range of shunt part is transferred into the limit of controlled bus voltage:

$$S_1 = \{UPFC / \|V_{pq}\| \leq 1.0, 0 \leq \theta_{pq} \leq 360^0, 0.95 \leq V_6 \leq 1.05\} \tag{6-4}$$

Here

$$S_1 \subseteq S \tag{6-5}$$

In our studies, the initial point is set to V_6=1.03 p.u., V_{pq}=0.1p.u. and θ_{pq} =0.0^0 . When the predictor μ=1, increase V_{pq} until μ=0; if μ is not equal to zero in the range of V_{pq}, the search stops at V_{pq}=1.0 p.u. Then if μ=0, change θ_{pq} and set V_{pq}=0.1p.u, repeat the process. Finally, change V_6 until the whole range of S_1 is searched.

6.4.2 Algorithm Effectiveness And Results

A large number of studies have been conducted which clearly illustrate the effectiveness and fast convergence of the proposed method on the IEEE 30-bus system. Here some key points are selected to verify the effectiveness of the algorithm. In the following discussions, V_6 is set to 1.03p.u. and θ_{pq} starts from 0.0^0 and V_{pq} is increased from V_{pq}=0.1p.u..

6.4.2.1 Comparison Between the Predictor μ and SVD Value

As the indictor μ is the key to predict the convergence of power flow with UPFC, the values of μ in Tables 6-1 and 6-2 are used to compare SVD values under different control parameters. From both tables, it is found that SVD is nearly equal to zero when μ tends to be zero while SVD is bigger than zero as μ is one, which clearly demonstrates that optimal multiplier μ can be used as the indicator to predict the collapse point of power flow with the UPFC. Other numerous computations all illustrate collapse points corresponding to the singular value of zero.

6.4.2.2 Maximum Regulating Capability of UPFC Control Parameters

Using the proposed method, the maximum regulating capability of UPFC control parameters has been drawn in Figures.6-1 and 6-2. In the diagrams, dotted blocks represent collapse points, solid lines represent the section of smooth regulating area and dotted lines means oscillating section. P is the power transferred from bus 6 to bus 8 whose line is installed with UPFC. The P is chosen to represent the maximum regulating capability under different the UPFC control parameter patterns. From the figures, it is found that there is a smooth regulating section where P is approximately linear with V_{pq}. Beyond the section, P oscillates with the increasing of V_{pq} until V_{pq} arrives at the collapse point. It also is found that V_{pq} has different regulating capabilities over P when with different phase angles. Comparing Figure 6-1(b) and Figure 6-2, they tend to diverge at different ways. The reason for such phenomena is that the shunt part of UPFC changes the Jacobian matrix element. From the figures, one can easily determine the maximum regulating capability of UPFC without causing system and UPFC collapse. For example, the transferred active power of line 6 - 8 can reach nearly 0.3 p.u. under the control of the UPFC with the parameters shown in Figure 6-1(a), while under the normal condition without the UPFC, the active power is 0.1 p.u.. This value of the active power is the maximum regulating capability of the UPFC under such control parameter pattern. Other diagrams represent different maximum regulating capabilities under various control parameter patterns.

Figures 6-1 and 6-2 illustrate the control effects of a single UPFC parameter on the regulated line power while Figures 6-3, 6-4 and 6-5 are about the control performances of multiparameters of the UPFC. From Figure 6-3, it can be seen that the relationship between the phase shift angle and the amplitude of the series voltage of the UPFC is highly non-linear, which makes the control of UPFC very complex. Figures 6-4 and 6-5 illustrate the maximum regions of the regulated line power by the multi-parameter control of the UPFC by using the proposed algorithm. The two diagrams can provide operators useful information about the control capability of the UPFC and the relevant regulated line power regions.

6.5 Summary

A new algorithm of computing the maximum regulating capability of UPFC has been presented in this chapter. The optimal multiplier μ used as the indicator has several advantages: (i) It is the by-product of optimal multiplier power flow without any additional computations; (ii) It strongly relates to the singularity of Jacobian matrix when the system tends to collapse. The proposed algorithm, which is a step-by-step calculation to obtain the discrete collapse points of UPFC parameters under different patterns, can provide the planners with the direct, quick and accurate method to define the maximum regulating capability of UPFC. The simulation results have verified the proposed approach. The computed the maximum regulating capability of UPFC and its thermal limit and other security limits are important constraints in the operation of a transmission system with embedded UPFCs. On the other hand, dynamic control capability and other factors in the applications of FACTS in power systems have been under vigorous studies by a number of researchers [21].

Table 6-1 List of the predictor μ and SVD under $\theta_{pq}=90.0^0$

cases ($\theta_{pq}=90.0^0$)	predictor μ	minimum singular value
$V_{pq}=0.1$ p.u	1.0	0.2020
$V_{pq}=0.13$ p.u	1.0	0.1972
$V_{pq}=0.15$ p.u	1.0	0.1766
$V_{pq}=0.18$ p.u	0.02833	0.0160
$V_{pq}=0.20$ p.u	0.00010	0.0002

Table 6-2 List of the predictor μ and SVD under $\theta_{pq}=180.0^0$

cases ($\theta_{pq}=180.0^0$)	predictor μ	minimum singular value
$V_{pq}=0.1$ p.u	1.0	0.1815
$V_{pq}=0.13$ p.u	1.0	0.1673
$V_{pq}=0.3$ p.u	0.1221	0.0058
$V_{pq}=0.36$ p.u	0.0	0.0003

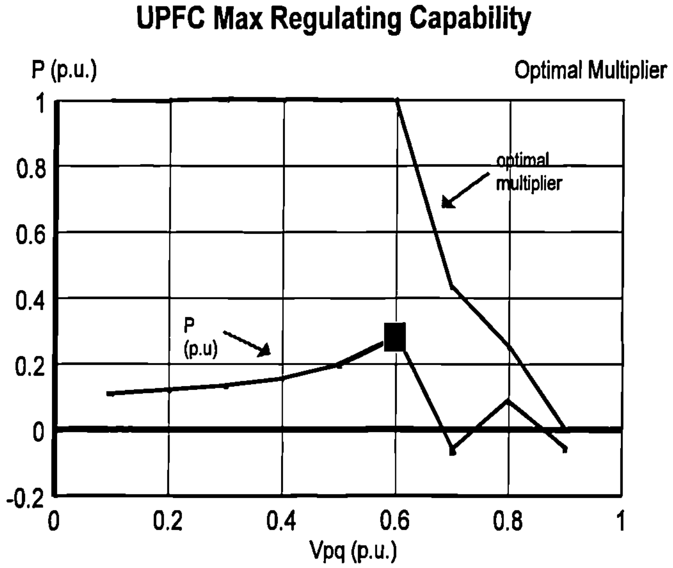


Figure 6-1(a) Regulating capability of active power vs. V_{pq} under $\theta_{pq}=0.0^0$ and $V_6=1.03$ p.u.

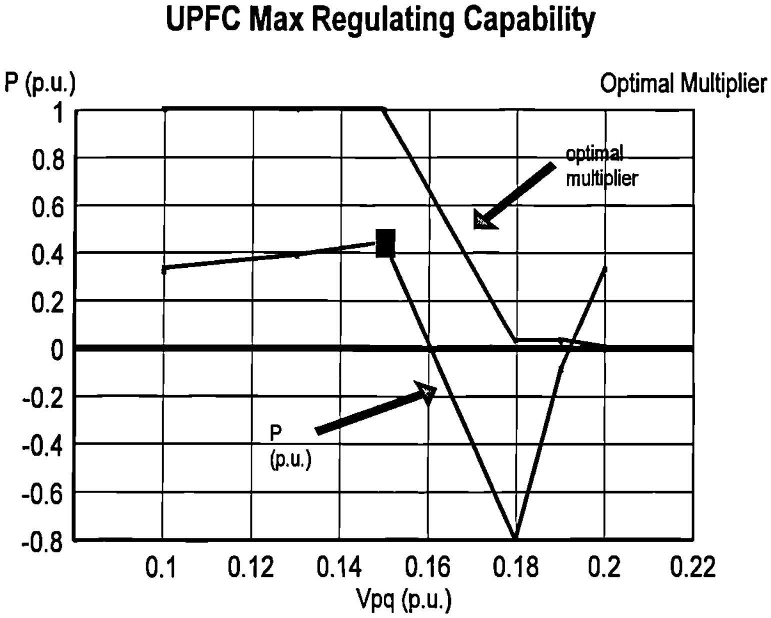


Figure 6-1(b) Regulating capability of active power vs. V_{pq} under $\theta_{pq}=90.0^0$ and $V_6=1.03$ p.u.

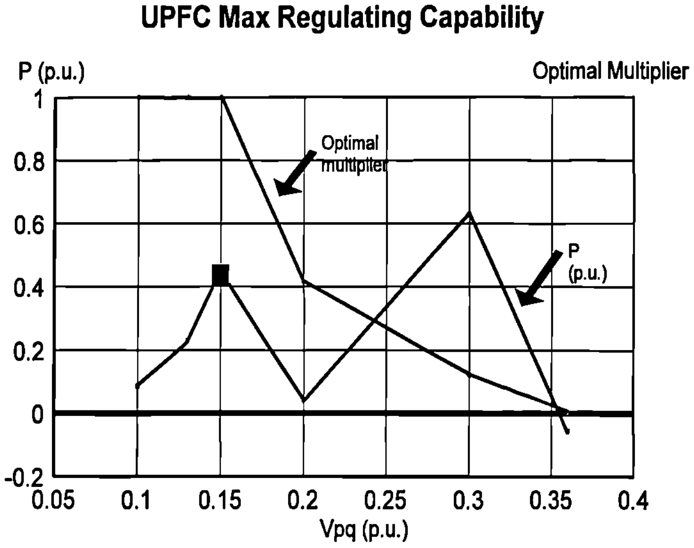


Figure 6-1(c) Regulating capability of active power vs. V_{pq} under $\theta_{pq}=180.0^0$ and $V_6=1.03$ p.u.

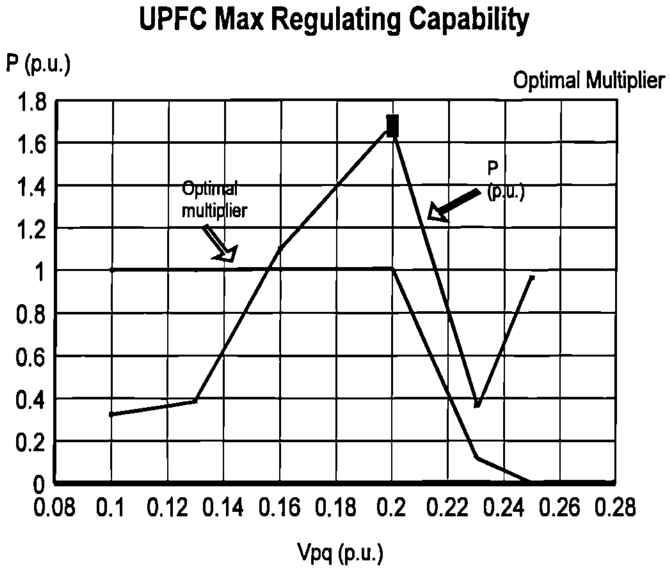


Figure 6-2 Regulating capability of active power vs. V_{pq} under $\theta_{pq}=90.0^0$ and $V_6=1.0$ p.u.

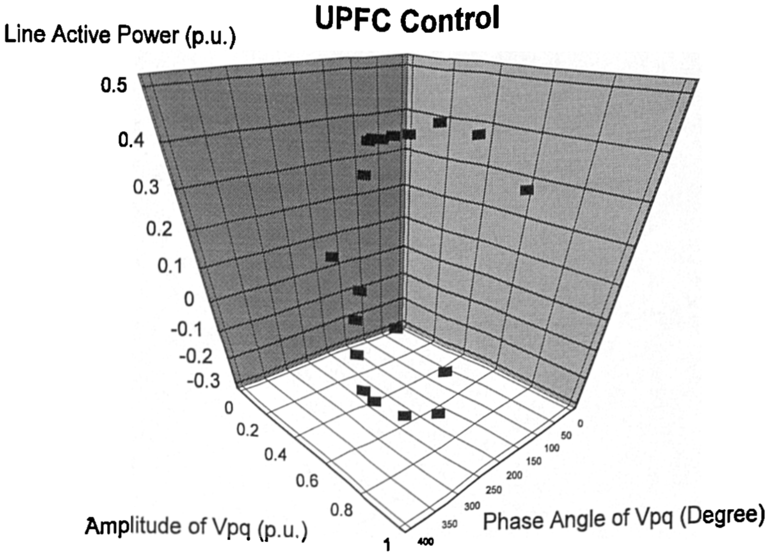


Figure 6-3 Diagram of UPFC control parameter space

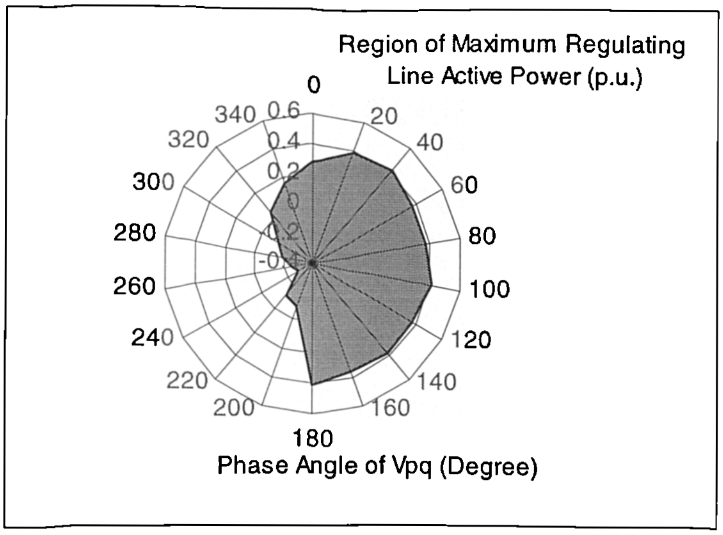


Figure 6-4 Maximum region of the regulated line active power by UPFC

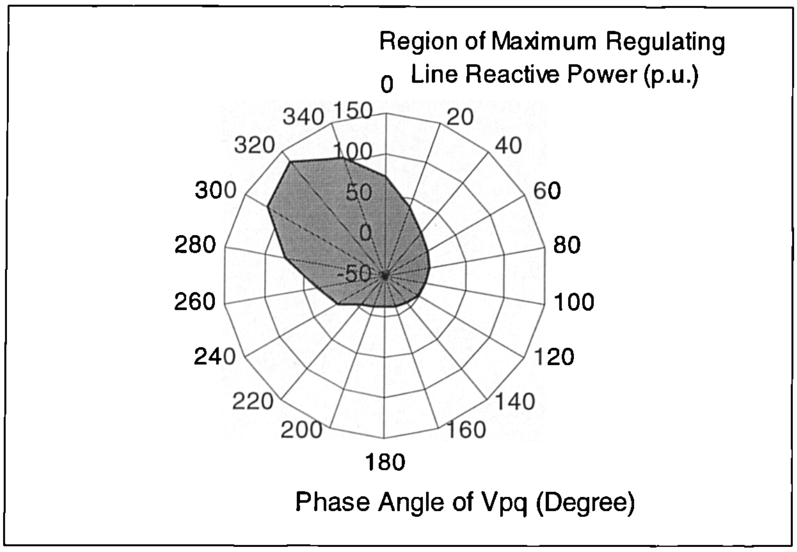


Figure 6-5 Maximum region of the regulated line reactive power by UPFC

Chapter 7

POWER FLOW AND VOLTAGE CONTROL BY USE OF UPFC

7.1 Introduction

The UPFC offers new horizons in terms of power system control, with the potential to independently control up to three power system parameters, for instance bus voltage, line active power and line reactive power. In Chapter 5, UPFC steady state model and its implementation in normal (open-loop) power flow has been investigated. With the application of such controllable devices, there is a need to ascertain the most appropriate power system control strategy both for an individual UPFC, and for their global co-ordination across a system. Controllable shunt compensation schemes, such as the SVC, have been extensively used on transmission system for the past decade, and the appropriate power system control strategies are now well established. Control strategies for controllable series devices, however, are significantly less developed, particularly for meshed power systems. Such devices are intrinsically different from shunt devices in that they potentially have a much greater effect on power flows, and must be able to accommodate the loss of the circuit into which the device is connected. In this respect, reference [32] presented an optimal power flow method to derive UPFC control to regulate line flow and at the same time to minimise power losses. A Newton-type algorithm for the control of power flow in electrical power networks has been developed in references [150].

Based on the proposed optimal multiplier based power flow for UPFC studies in chapter 5 and power injection model, this chapter further develops the idea of power injection model to derive control parameters for UPFC to achieve the required line active power control and bus voltage support. The proposed method offers a number of advantages: it does not change the symmetrical structures of Jacobian matrix, avoids the initialisations of control parameters and can cover a wide control range of UPFC due to the characteristics of optimal multiplier power flow algorithms employed. The effectiveness of the proposed local control method will be demonstrated on a meshed power system.

7.2 Power Injection Based Power Flow Control Method

7.2.1 General Concept

For relieving thermal and voltage transmission constraints (i.e. power flow control and voltage support) [151, 152, 153], an overall UPFC control strategy is envisaged which involves (1) a central controller issuing setpoint voltage and circuit real power flow settings, and (2) local UPFC controllers to enable the UPFC to achieve the required setpoints. This paper describes a novel method for UPFC local control - power injection model based control co-ordination algorithm (PIM).

As discussed in chapter 5, the UPFC represented by two voltage sources of series part and shunt part is often transformed into a pair of power injections ($P_{i(inj)}$, $Q_{i(inj)}$) ($P_{j(inj)}$, $Q_{j(inj)}$), as shown in Figure 7-1. From the view point of effects of these power injections on the system, $Q_{i(inj)}$ can be independently regulated to support busbar voltage connected at the shunt part, $P_{i(inj)}$ and $P_{j(inj)}$ are used to manipulate line active power with equal magnitude but at reverse direction and $Q_{j(inj)}$ (when UPFC loss is neglected) can control both j busbar voltage and line reactive power. Under lossless conditions, the UPFC operating condition can be specified by the following three quantities shown in Figure 7-1: Q_{sh} - reactive power supplied through shunt current; Q_{ser} - reactive power supplied through series voltage injection and P_{dc} - real power supplied across the dc-link from shunt to series inverters.

In most applications, the central controller places on the UPFC a requirement to regulate two power system parameters, namely busbar voltage and circuit real power flow. For a UPFC with three degrees of freedom, a spare degree of freedom is available which may be used in an advantageous manner, for instance, to minimise device rating requirements. This chapter introduces some preliminary concepts on the possible utilisation of this spare degree of freedom. An initial algorithm, referred to as the PIM algorithm, applies the constraint $Q_{j(inj)}$ =0, where $Q_{j(inj)}$ relates to the power injection model of the UPFC. This enables the PIM algorthim to be formulated based on: (a) Use $Q_{i(inj)}$ to control bus voltage V_i and (b) use $P_{i(inj)}$ and $P_{j(inj)}$ to control the circuit real power. However, the impact of non-zero value of $Q_{j(inj)}$ will also be discussed later in the chapter.

7.2.2 Decoupled Rectangular Co-Ordinate Power Flow Equations

In PIM, the foundation is the decoupled rectangular co-ordinate power flow equations (7-1) and (7-2):

$$[\Delta P / e] = [B'][\Delta f] \tag{7-1}$$

$$[\Delta Q / e] = [B''][\Delta e] \tag{7-2}$$

Where, the elements of the matrices $[B']$ and $[B'']$ are the negative of the elements of the imaginary part of bus admittance matrix $[-B]$.

7.2.3 Closed-Loop Voltage Control Strategy by Reactive Power Injection

Assuming that the controlled busbar voltage magnitude is V_i^{spe}, then the control strategy is as follows:

Convergence condition:

$$Max\{V_i^{spe} - V_i^k\} \leq \varepsilon \tag{7-3}$$

Iteration process:

$$\Delta Q_{i(inj)}^k = \Delta Q_{i(inj)}^{k-1} - B_{ii} \Delta e_i^k e_i^k \tag{7-4}$$

$$\Delta e_i^k = e_i^k - e_i^{k-1} \tag{7-5}$$

$$e_i^k = V_i^{spe} \cos\theta_i^{k-1} \tag{7-6}$$

$$\theta_i^{k-1} = a\tan\left(\frac{f_i^{k-1}}{e_i^{k-1}}\right) \tag{7-7}$$

where i controlled busbar

k the kth power flow iteration

$\Delta Q_{i(inj)}^k$ the incremental reactive power injection needed to control busbar voltage at the busbar i

B_{ii} busbar admittance of busbar i

ε tolerance of controlled voltage

7.2.4 Closed-Loop Line Transfer Active Power Control Strategy by Active Power Injections

Assuming that the control objective of line transfer active power is P_l^{spe}, then the proposed controller is presented as:

Convergence condition:

$$Max\{P_l^{spe} - P_l^k\} \leq \sigma \tag{7-8}$$

Iteration process

$$\Delta P_{i(inj)}^k = \Delta P_{i(inj)}^{k-1} - (P_l^{spe} - P_l^{k-1}) / (w_{li} / e_i^{k-1} - w_{lj} / e_j^{k-1}) \tag{7-9}$$

$$\Delta P_{j(inj)}^k = -\Delta P_{i(inj)}^k \tag{7-10}$$

where, l representing controlled line

$\Delta P_{i(inj)}^k$ the incremental busbar active power injection at busbar i needed to control line transfer power

$\Delta P^{k}_{j(inj)}$ the incremental busbar active power injection at busbar j needed to control line transfer power

$w_{li,}w_{lj}$ weight factors of line l transfer active power to busbar active power injections at busbar i and j,

σ tolerance of controlled line transfer power

The weight factors $w_{li,}w_{lj}$ are formulated from the linear relationship of line active power and busbar active power injections. The incremental value of line l active power as ΔP_l can be expressed in terms of changes in busbar active power injections as follows:

$$\Delta P_l = \frac{\partial P_l}{\partial P_1}\Delta P_1 + \cdots + \frac{\partial P_l}{\partial P_i}\Delta P_i + \cdots + \frac{\partial P_l}{\partial P_n}\Delta P_n \qquad (7\text{-}11)$$

While the partial derivatives of the line active powers with respect to injections can be expressed:

$$\frac{\partial P_l}{\partial P_i} = \frac{\partial P_l}{\partial f_1}\frac{\partial f_1}{\partial P_i} + \cdots + \frac{\partial P_l}{\partial f_i}\frac{\partial f_i}{\partial P_i} + \cdots + \frac{\partial P_l}{\partial f_n}\frac{\partial f_n}{\partial P_i} \qquad (7\text{-}12)$$

Therefore, combing the above two equations, ΔP_l is represented by following matrix form:

$$\Delta P_l = \begin{bmatrix} \dfrac{\partial P_l}{\partial f_1} \cdots \dfrac{\partial P_l}{\partial f_i} \cdots \dfrac{\partial P_l}{\partial f_n} \end{bmatrix} \begin{bmatrix} \dfrac{\partial f_1}{\partial P_1} \cdots \dfrac{\partial f_1}{\partial P_i} \cdots \dfrac{\partial f_1}{\partial P_n} \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ \dfrac{\partial f_i}{\partial P_1} \cdots \dfrac{\partial f_i}{\partial P_i} \cdots \dfrac{\partial f_i}{\partial P_n} \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ \dfrac{\partial f_n}{\partial P_1} \cdots \dfrac{\partial f_n}{\partial P_i} \cdots \dfrac{\partial f_n}{\partial P_n} \end{bmatrix} \begin{bmatrix} \Delta P_1 \\ \cdots\cdot \\ \cdots\cdot \\ \Delta P_i \\ \cdots\cdot \\ \cdots\cdot \\ \Delta P_j \\ \cdots\cdot \\ \cdots\cdot \\ \Delta P_n \end{bmatrix}$$

$$= \begin{bmatrix} \frac{1}{e_1}\frac{\partial P_l}{\partial f_1} \cdots \frac{1}{e_i}\frac{\partial P_l}{\partial f_i} \cdots \frac{1}{e_n}\frac{\partial P_l}{\partial f_n} \end{bmatrix} \begin{bmatrix} \frac{\partial f_1}{\partial P_1} \cdots \frac{\partial f_1}{\partial P_i} \cdots \frac{\partial f_1}{\partial P_n} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ \frac{\partial f_i}{\partial P_1} \cdots \frac{\partial f_i}{\partial P_i} \cdots \frac{\partial f_i}{\partial P_n} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ \frac{\partial f_n}{\partial P_1} \cdots \frac{\partial f_n}{\partial P_i} \cdots \frac{\partial f_n}{\partial P_n} \end{bmatrix} \begin{bmatrix} \Delta P_1 / e_1 \\ \cdots\cdots \\ \cdots\cdots \\ \Delta P_i / e_i \\ \cdots\cdots \\ \cdots\cdots \\ \Delta P_j / e_j \\ \cdots\cdots \\ \cdots\cdots \\ \Delta P_n / e_n \end{bmatrix}$$

$$= \begin{bmatrix} \frac{1}{e_1}\frac{\partial P_l}{\partial f_1} \cdots \frac{1}{e_i}\frac{\partial P_l}{\partial f_i} \cdots \frac{1}{e_n}\frac{\partial P_l}{\partial f_n} \end{bmatrix} [S] \begin{bmatrix} \Delta P_1 / e_1 \\ \cdots\cdots \\ \cdots\cdots \\ \Delta P_i / e_i \\ \cdots\cdots \\ \cdots\cdots \\ \Delta P_j / e_j \\ \cdots\cdots \\ \cdots\cdots \\ \Delta P_n / e_n \end{bmatrix} \qquad (7\text{-}13)$$

where,

$$P_l = G_{ij}(e_i e_j + f_i f_j - e_j^2 - f_j^2) + B_{ij}(e_i f_j - e_j f_i) \qquad (7\text{-}14)$$

$$\frac{\partial P_l}{\partial f_i} = G_{ij} f_j - B_{ij} e_j \qquad (7\text{-}15)$$

$$\frac{\partial P_l}{\partial f_j} = G_{ij} f_i - 2G_{ij} f_j + B_{ij} e_i \qquad (7\text{-}16)$$

$$[S]=[B']^{-1} \tag{7-17}$$

7.2.5 Solution of UPFC Parameters

Based on the results, the pair of power injections $(P_{i(inj)}, Q_{i(inj)})$ and $(P_{j(inj)}, Q_{j(inj)})$ derived from the closed-loop controllers can be used to obtain the values of two voltage sources of the UPFC. During this stage of calculation, these power injections and UPFC control parameters are linked through the following four equations obtained from the transformation process of UPFC models from voltage sources to power injections:

$$P_{i(inj)} = G_{ij}(-V_{pq}^2 - 2e_i e_{pq} - 2f_i f_{pq} + e_j e_{pq} + f_j f_{pq}) + B_{ij}(e_j f_{pq} - f_j e_{pq}) \tag{7-18}$$

$$Q_{i(inj)} = G_{ij}(e_i f_{pq} - f_i e_{pq}) + B_{ij}(e_i e_{pq} + f_i f_{pq}) - G_{i0}(-f_i e_{sh} + e_i f_{sh}) + B_{i0}(V_i^2 - e_i e_{sh} - f_i f_{sh}) \tag{7-19}$$

$$P_{j(inj)} = G_{ij}(e_j e_{pq} + f_j f_{pq}) + B_{ij}(f_j e_{pq} - e_j f_{pq}) \tag{7-20}$$

$$Q_{j(inj)} = G_{ij}(f_j e_{pq} - e_j f_{pq}) - B_{ij}(e_j e_{pq} + f_j f_{pq}) \tag{7-21}$$

$$\begin{aligned} P_{dc} &= \mathrm{Re}\left[\dot{V}_{pq}\left(\frac{\dot{V}_i + \dot{V}_{pq} - \dot{V}_j}{Z_{ij}}\right)^*\right] \\ &= G_{ij}(V_{pq}^2 + e_i e_{pq} - e_j e_{pq} + f_i f_{pq} - f_j f_{pq}) + B_{ij}(e_i f_{pq} - e_j f_{pq} - f_i e_{pq} + f_j e_{pq}) \end{aligned} \tag{7-22}$$

$$\begin{aligned} Q_{ser} &= \mathrm{Im}\left[\dot{V}_{pq}\left(\frac{\dot{V}_i + \dot{V}_{pq} - \dot{V}_j}{Z_{ij}}\right)^*\right] \\ &= G_{ij}(e_i f_{pq} - e_j f_{pq} - f_i e_{pq} + f_j e_{pq}) - B_{ij}(V_{pq}^2 + e_i e_{pq} - e_j e_{pq} + f_i f_{pq} - f_j f_{pq}) \end{aligned} \tag{7-23}$$

$$P_{i0} = G_{i0}(V_i^2 - e_i e_{sh} - f_i f_{sh}) + B_{i0}(e_i f_{sh} - f_i e_{sh}) \tag{7-24}$$

$$Q_{i0} = G_{i0}(e_i f_{sh} - f_i e_{sh}) + B_{i0}(e_i e_{sh} + f_i f_{sh} - V_{sh}^2) \quad (7\text{-}25)$$

where $S_{i0}=P_{i0}+jQ_{i0}$ is the power injection of shunt side of the UPFC at the i busbar, P_{dc} is the power transfer from shunt side to series side, S_i and S_j are two power injections transformed from the series voltage at i and j busbars. The all formulae are derived under the assumption of neglecting power loss inside the UPFC, i.e $P_{io}=P_{dc}$.

where

$$G_{ij} + jB_{ij} = \frac{1}{R_{ij} + jX_{ij}} = \frac{1}{Z_{ij}} \quad (7\text{-}26)$$

$$G_{i0} + jB_{i0} = \frac{1}{R_{i0} + jX_{i0}} = \frac{1}{Z_{i0}} \quad (7\text{-}27)$$

For the simplicity, if the resistance of shunt and series transformers of the UPFC is neglected, we can obtain the shunt and series voltage source parameters of the UPFC based on the following equations:

$$\begin{bmatrix} e_{pq} \\ f_{pq} \end{bmatrix} = \begin{bmatrix} B_{ij} f_j & -B_{ij} e_j \\ -B_{ij} e_j & -B_{ij} f_j \end{bmatrix}^{-1} \begin{bmatrix} P_{j(inj)} \\ Q_{j(inj)} \end{bmatrix} \quad (7\text{-}28)$$

$$V_{pq} = \sqrt{e_{pq}^2 + f_{pq}^2} \quad (7\text{-}29)$$

$$\theta_{pq} = a\tan\left(\frac{f_{pq}}{e_{pq}}\right) \quad (7\text{-}30)$$

Then we have

$$P_{dc} = \left[-f_{pq}(e_i - e_j) + e_{pq}(f_i - f_j) \right] / X_{ij} \quad (7\text{-}31)$$

Next set

$$P_{i0} = P_{dc} \tag{7-32}$$

$$P_{i0} = (f_i e_{sh} - e_i f_{sh}) / X_{i0} \tag{7-33}$$

Then

$$f_{sh} = (f_i e_{sh} - P_{dc} X_{i0}) / e_i \tag{7-34}$$

$$e_{sh} = \frac{Q_{i(inj)} + \frac{V_i^2}{X_{i0}} + \frac{f_i P_{dc}}{e_i} + \frac{e_i e_{pq} + f_i f_{pq}}{X_{ij}}}{\frac{e_i}{X_{i0}} + \frac{f_i^2}{X_{i0} e_i}} \tag{7-35}$$

$$V_{sh} = \sqrt{e_{sh}^2 + f_{sh}^2} \tag{7-36}$$

$$\theta_{sh} = a\tan(\frac{f_{sh}}{e_{sh}}) \tag{7-37}$$

Then we have

$$Q_{sh} = Q_{i0} = (V_i^2 - e_i e_{sh} - f_i f_{sh}) / X_{i0} \tag{7-38}$$

$$Q_{ser} = \left[e_{pq}(e_i - e_j) + f_{pq}(f_i - f_j) + V_{pq}^2\right] / X_{ij} \tag{7-39}$$

$$S_{sh} = \sqrt{P_{dc}^2 + Q_{sh}^2} \tag{7-40}$$

$$S_{ser} = \sqrt{P_{dc}^2 + Q_{ser}^2} \tag{7-41}$$

7.3 Test Results

In order to fully asses the control aspect, the chapter employs the test system which has been carefully constructed in references [154, 155, 156, 157] and based on a practical system with an aim to provide representative thermal and voltage transmission constraints, and to be able to accommodate a range of generation scenarios.

7.3.1 Test System and Un-Reinforced Studies

A single-line diagram of the HV circuits of the test system is shown in Figure7-2. It comprises: (i) 13 HV buses with attached load and fixed shunt compensation; (2) 42 circuits connecting the HV buses, arranged as a combination of single and double circuit lines. All HV circuits have a designated thermal rating and an X/R ratio of 10. All but 3 of lines can be outaged under contingency conditions; (iii) 10 LV buses with attached generation with transformer connection to HV buses and (iv) controlled shunt compensation applied to 5 of the HV buses. There are twelve key double-circuits associated with the boundary A. In order to allow for alternative generation patterns, the generation at each location can be increased by up to 20% from the baseline generation pattern [158, 159].

In order to establish a common base for comparison of reinforcement strategies, the following design criteria are applied: (i) All circuit current flows to be within their thermal capabilities under intact, single-circuit outage and double-circuit outage conditions and (ii) All HV bus voltages to be within the range 0.975-1.025pu under intact system conditions. All HV bus voltages to be within the range 0.95-1.025pu under single-circuit and double-circuit outage conditions, and in particular, before any adjustment to generator step-up transformer tap ratios.

The power flow results of two operation conditions and outages on the test system are listed in Tables 7-1 and 7-2.

Default and Scenario A are two typical operating conditions, the former is normal generation-load pattern, the latter is the result of 20% increase in generation of the upper part of network based on Default which leads to a big increase of power transfer across boundary A.

From Tables 7-1 and 7-2, it is seen that the transfer capability across boundary A is limited by violations of line thermal and busbar voltage constraints and the power sharing among the line across boundary A is unbalanced and also there is enough space left for these lines to transfer the given power without exceeding thermal limits. If the system is designed to transfer the given power across boundary A under these operating points, there are two basic ways which can be used: one is to build new transmission lines or replace the line with a new and higher thermal limit transmission line; another is to install control devices to share loads among the boundary lines, in this case, the total transfer capability of this method is determined by the sum of thermal limits of these lines and thus it enhances the system transfer capability. Therefore, UPFCs can expect to play an important role in enhancing the system in this aspect.

All the simulation results of this section are studied based on cases 1 and 2. The definitions of cases 1 and 2 are: Case 1 is 'Default' operation condition with outage of two lines 60-100 and 60-120; Case 2 is 'Scenario A' operation condition with outage of line 40-70.

7.3.2 Convergence Analysis of Controlled Power Flow

The convergence of the proposed controlled power flow has been tested in a large number of cases under different system conditions and with various number of UPFCs. All these test results clearly show the quadratic convergence of the proposed PIM. This is largely because PIM does not change the features such as optimal bus ordering, sparisity and symmetric properties of Jacobian matrix and quick forward and backward substitutions. Also as discussed in chapter 5, the power flow method adopted is based on optimal multiplier algorithms which offers a number of advantages.

As an example, Figures 7-3, 7-4, and 7-5 illustrate the convergence of the proposed PIM with a UPFC installed along line 90-60 under case 2. The control objective is V_{90}=1.01 p.u. and P_{90-60} =-17.0 p.u.. The actual results of controlled states with a UPFC obtained by PIM are

V_{90}=1.00984 p.u. and P_{90-60} =-17.034 p.u.. The PIM converges at 12 iterations. Although the initial mismatches of bus power injections are big owing to participation of additional power injections, they tend to converge quickly. Figures. 7-4 and 7-5 illustrate the mismatches of controlled bus voltage and line active power.

7.3.3 Control Performance Analysis

In order to verify the proposed PIM, various schemes of controlling busbar voltage and line transfer power have been studied. Some results are shown in Tables 7-3 and 7-4. In these tables, PIM not only shows its satisfactory ability of tracing control objectives, but also derives UPFC control parameters directly without any initial assumptions at local modes.

A single UPFC installed along line 90-60 under case 2 is studied to present the performances of PIM using different control objectives and the mappings of power injections of PIM and real parameters of UPFC, which can provide information about rating of UPFC. The different control objectives are designed to increase or decrease the specified value around the operating points. Under case 2, V_{90}=0.96884 p.u., P_{90-60}=-20.786 p.u.. Four control cases are demonstrated in Table 7-3, which gives the actual results of controlled states and its UPFC parameters. From the table, it is seen that the PIM can handle a wide range of control objectives without losing accuracy. For instance, the amplitude of V_{pq} can vary from 0.0498 to 0.1291 p.u. and its phase changes from 81.30^0 to 261.45^0, which is difficult to be handled by conventional methods. Furthermore, Table 7-4 presents the mapping of power injections of the proposed method and the parameters of UPFC, which justifies effectiveness of the PIM. Although the power injections are obtained through decoupled control of busbar voltage and line active power, PIM links these power injections using the UPFC internal relations and thus simulates the effects of the UPFC. These mappings provide the foundation of determining the rating of UPFC.

Furthermore, multi-UPFCs have also been investigated. For example, Table 7-5 presents the control performance of PIM under cases 1 and 2 with two UPFCs installed along lines 50-60 and 90-60, respectively. From both tables, it can be clearly seen that PIM can achieve different specified control objectives without any initial assumptions of UPFC parameters.

The PIM co-ordinates the UPFCs in the process of designing controllers in terms of power injections.

In order to verify the proposed control algorithm under contingency, some outage operating conditions are used to evaluate the performance of the UPFC control on the test network. Based on cases 1 and 2 of Tables 7-1 and 7-2, Table 7-6 gives the system performances with the installations of UPFCs. Investigation shows that if the violations of their voltage limits and line thermal limits of both cases are totally alleviated, it needs two UPFCs installed along lines 50-60 and 90-60. The results are summarised in Table 7-6, in which, both line thermal limit violations have been effectively alleviated and power sharing among lines tends to balance thus increasing power transfer capability across A boundary without constraint violations. This also shows that co-ordination of the UPFCs at different locations for solving power sharing and increasing power transfer has been achieved by PIM.

7.3.4 The Effect of $Q_{j(inj)}$

In the initial study of the proposed PIM, $Q_{j(inj)}$ is assumed to be zero, which is a special case of UPFC control. Because $Q_{j(inj)}$ can be designed to control both j bus voltage and line reactive power transmission, if $Q_{j(inj)}$ is designed to only control j bus voltage, their relationship can be defined by bus voltage and reactive power injection equations (7-3)~(7-7). However, V_j can be controlled through V_{pq} and V_i. If $Q_{j(inj)}$ is used to regulate line transfer reactive power, their relationship is highly non-linear and it is recommended not to do so [160, 161]. But it is necessary to investigate the effects of $Q_{j(inj)}$ on the PIM so as to better use the spare degree. Table 7-7 are the results considering $Q_{j(inj)}$. The results are based on case 2 with one UPFC installation along line 90-60. From condition 1 to condition 6, control objective is set as: V_{90}=0.99 p.u., $P_{90\text{-}60}$=-23.0 p.u., while $Q_{j(inj)}$ varies from -8.0 p.u. to 8.0 p.u..

From the results of table 7-7, it is shown that $Q_{j(jinj)}$ does not affect the controlled states of PIM, that is V_{90} and $P_{90\text{-}60}$. All cases have achieved their control objective within tolerance. With the increase of $Q_{j(inj)}$ from -8.0 p.u. to 8.0 p.u., system state V_{60} increases from 1.01166 p.u. to 1.02810 p.u., while $Q_{90\text{-}60}$ decreases from 4.595 p.u. to 3.301 p.u.. Conditions 2 and 3 give smaller rating of UPFC compared to condition 4. All these show that $Q_{j(inj)}$ may affect j bus voltage, line reactive power transmission and rating of UPFC. How to determine the best $Q_{j(inj)}$ depends on the compromise among these factors. For example, effectively, $Q_{j(inj)}$ can be optimised to minimise the rating of UPFC.

7.4 Summary

In Chpter 5, UPFC steady state model and its implementation in normal (open-loop) power flow has been investigated. This chapter further develops the method for the steady state control of UPFC for power flow control and voltage support. The proposed power injection power flow control can be effectively used to derive UPFC control parameters to achieve the required control objectives. The effectiveness of the proposed local control method has been demonstrated on a meshed power system derived from a practical system.

Table 7-1 Power flow results with contingence without UPFC

case	operating condition	outage line	transfer capability across A boundary	lowest voltage (p.u)	violations of line thermal limits and voltage limits
case 1	Default	line 60—100 line 60—120	10056MW	V_{90}=0.94126	line 50-60 106.5% line 60—90 104.0%
case 2	Scenario A	line 40-70	13154MW	V_{50}=0.95764	line 50-60 108.4% line 60-90 108.49%

Table 7-2 Unbalanced power sharing among transmission lines across the A boundary

	case (without UPFCs)			
	case 1		case 2	
line	transfer active power (MW)	percentage of thermal limit	transfer active power (MW)	percentage of thermal limit
60—90	592.9	61.60%	634.5	63.91%
60—90	307.7	63.93%	329.3	66.89%
60—90	2002.0	104.00%	2142.6	108.49%
50—60*	-1010.3	106.51%	-996.9	108.40%

Table 7-3 Bus voltage and line power flow performances controlled by UPFC using the proposed PIM (The angles of UPFC sources are with respect to the angle of slack bus voltage of the system)

control case	given control values (p.u)	actual control values (p.u)	parameters of UPFC (p.u)
1	$V_{90}=0.99$ line 90-60: P=-18.78	$V_{90}=0.9898$ line 90-60: P=-18.79	UPFC for 90-60: $V_{pq}=0.0672\angle 261.39^0$ $V_{sh}=1.0106\angle -23.52^0$
2	$V_{90}=1.01$ line 90-60: P=-17.0	$V_{90}=1.0098$ line 90-60: P=-17.03	UPFC for 90-60: $V_{pq}=0.1291\angle 261.45^0$ $V_{sh}=1.0576\angle -21.72^0$
3	$V_{90}=0.99$ line 90-60: P=-23.0	$V_{90}=0.9895$ line 90-60: P=-22.96	UPFC for 90-60: $V_{pq}=0.0613\angle 81.3^0$ $V_{sh}=1.0068\angle -27.42^0$
4	$V_{90}=0.95$ line 90-60: P=-18.78	$V_{90}=0.9498$ line 90-60: P=-18.79	UPFC for 90-60: $V_{pq}=0.0498\angle 261.30^0$ $V_{sh}=0.9177\angle -24.15^0$

Table 7-4 The impact of PIM on the UPFC operating condition(all in p.u., the series reactance of the UPFC is assumed to be 0.01p.u.; the shunt reactance is 0.005; V_i represents the voltage of bus 90; P_{line} and Q_{line} are powers transferred from bus 90 to bus 60.)

control case	system conditions			power injection model conditions			UPFC conditions		
	P_{line}	Q_{line}	V_i	$Q_{i(inj)}$	$P_{j(inj)}$	$Q_{j(inj)}$	Q_{sh}	P_{dc}	Q_{ser}
1	-18.79	1.894	0.9898	2.8293	-4.9838	0.0	-4.0784	-0.3255	1.5766
2	-17.03	2.276	1.0098	7.4493	-9.6091	0.0	-9.6222	-0.4107	3.3812
3	-22.96	3.943	0.9895	4.8211	4.5311	0.0	-3.4176	0.3654	-1.131
4	-18.79	-0.188	0.9498	-7.0189	-3.6739	0.0	6.0981	-0.3693	1.1008

Table 7-5 The impact of PIM on the UPFC operating condition (two UPFCs installation)

case	UPFC locations	given control values (p.u)	actual control values (p.u)
1	line 50-60 line 90-60	V_{50}=1.0 line 50-60: P=-9.0 V_{90}=0.99 line 90-60: P=-17.8	V_{50}=1.0023 line 50-60: P=-8.967 V_{90}=0.99473 line 90-60: P=-17.65
2	line 50-60 line 90-60	V_{50}=1.0 line 50-60: P=-8.5 V_{90}=0.98 line 90-60: P=-17.5	V_{50}=1.00238 line 50-60: P=-8.476 V_{90}=0.98205 line 90-60: P=-17.405

Table 7-6 Summary of power flow results with UPFC

case	UPFC location line	lowest voltage (p.u.)	line power flow results		
			line	active power (MW)	thermal limit (%)
case 1	50-60 60-90	V_{70}=0.982	60-90	940.4	95.51%
			60-90	488.0	99.12%
			60-90	1832.1	93.81%
			50-60	-896.7	91.87%
case 2	50-60 60-90	V_{90}=0.981	60-90	917.3	92.08%
			60-90	476.0	96.36%
			60-90	1785.5	90.93%
			50-60	-847.6	88.74%

Table 7-7(a) Performance of PIM affected by $Q_{j(inj)}$

condition	1	2	3
$Q_{j(inj)}$	-8.0	-4.0	-2.0
V_{90}	0.98949	0.9895	0.9895
V_{60}	1.01166	1.01583	1.0179
P_{90-60}	-22.969	-22.966	-22.960
Q_{90-60}	4.595	4.267	4.105
V_{pq}	$0.1234\angle 143.4^0$	$0.0816\angle 123.04^0$	$0.0668\angle 105.22^0$
V_{sh}	$0.9753\angle -28.46^0$	$0.9909\angle -27.94^0$	$0.9989\angle -27.68^0$
P_{dc}	2.8405	1.5982	0.9790
Q_{sh}	2.8227	-0.2768	-1.8494
Q_{ser}	0.3642	-0.6082	-0.9206
S_{sh}	4.0045	1.6220	2.0926
S_{ser}	2.8638	1.7100	1.3439

Table 7-7(b) Performance of PIM affected by $Q_{j(inj)}$

case	4	5	6
$Q_{j(inj)}$	0.0	2.0	8.0
V_{90}	0.9895	0.9895	0.98949
V_{60}	1.01996	1.02201	1.02810
P_{90-60}	-22.962	-22.96	-22.955
Q_{90-60}	3.943	3.781	3.301
V_{pq}	$0.0613\angle 81.3^0$	$0.0672\angle 57.63^0$	$0.1180\angle 21.48^0$
V_{sh}	$1.0068\angle -27.42^0$	$1.0147\angle -27.18^0$	$1.0368\angle -26.56^0$
P_{dc}	0.3654	-0.2419	-1.7038
Q_{sh}	-3.4176	-4.9797	-9.3468
Q_{ser}	-1.1312	-1.2425	-1.3839
S_{sh}	3.4370	4.9856	9.5008
S_{ser}	1.1887	1.2658	2.1951

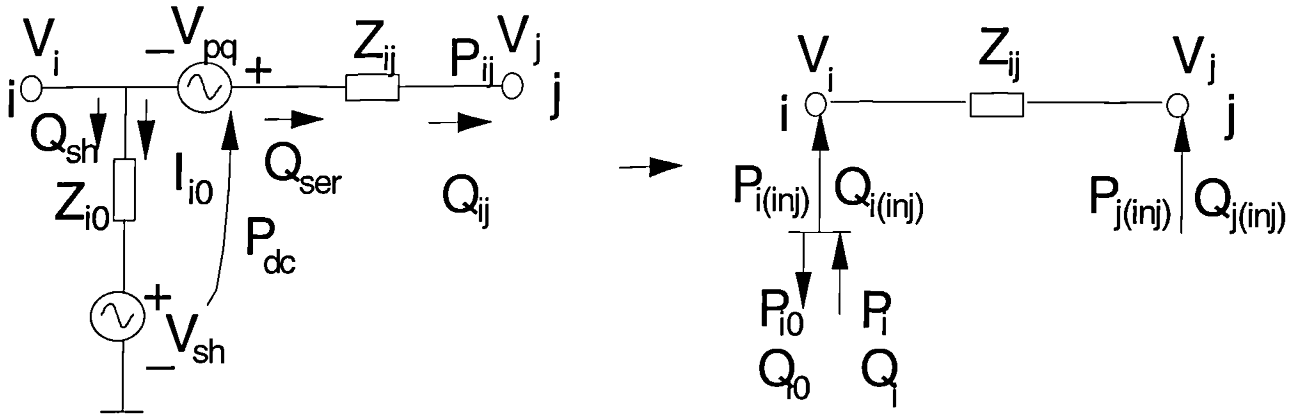


Figure 7-1 UPFC voltage source model and its power injection transformation

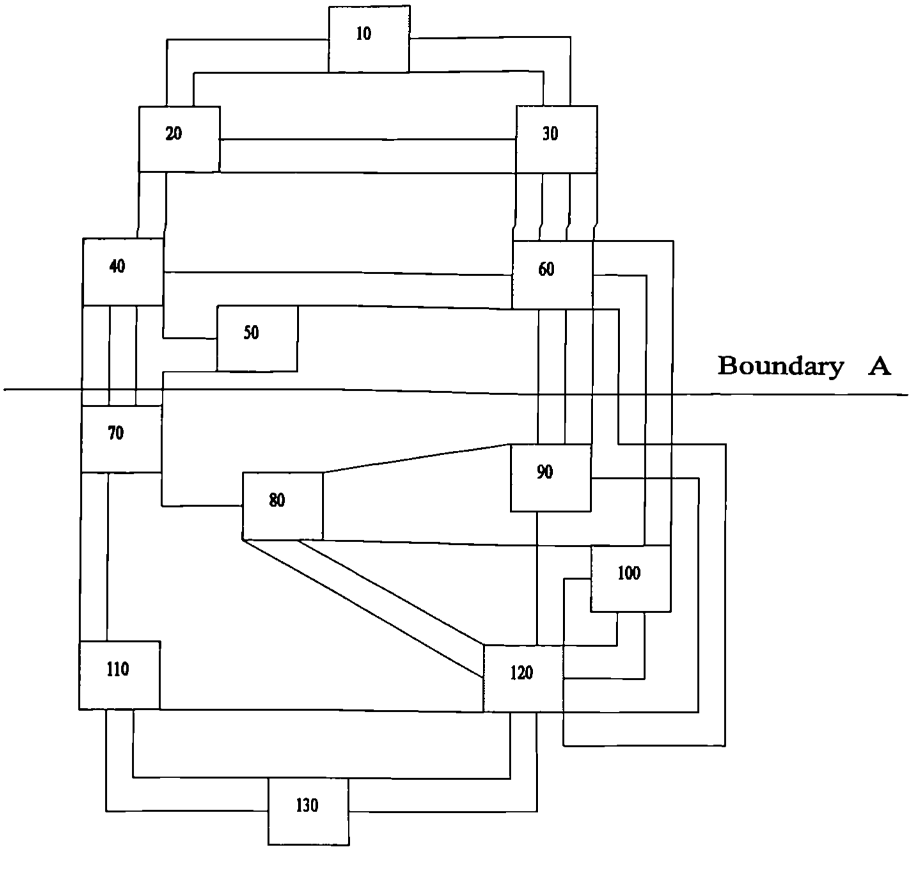


Figure 7-2 The meshed test network

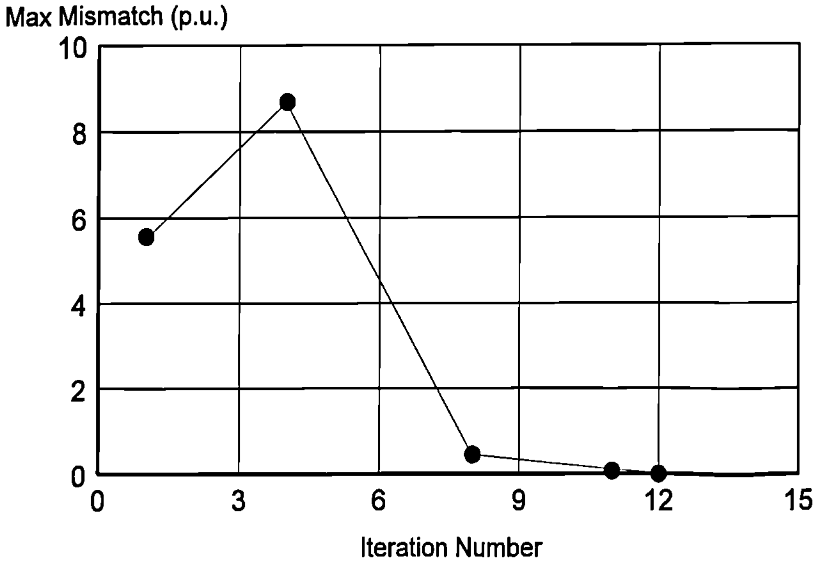


Figure 7-3 Maximum power mismatch vs. iteration number in PIM with one UPFC

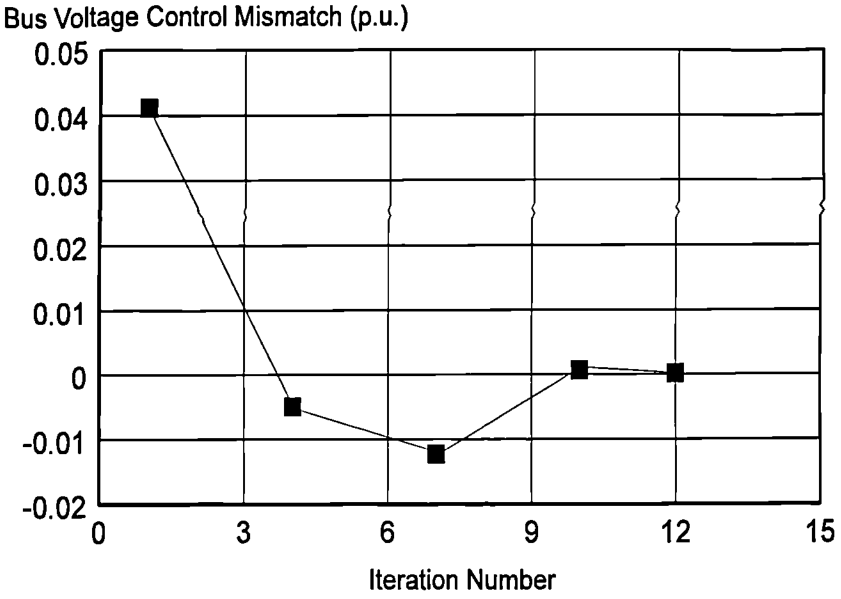


Figure 7-4 Bus voltage control mismatch vs. iteration number in PIM with one UPFC

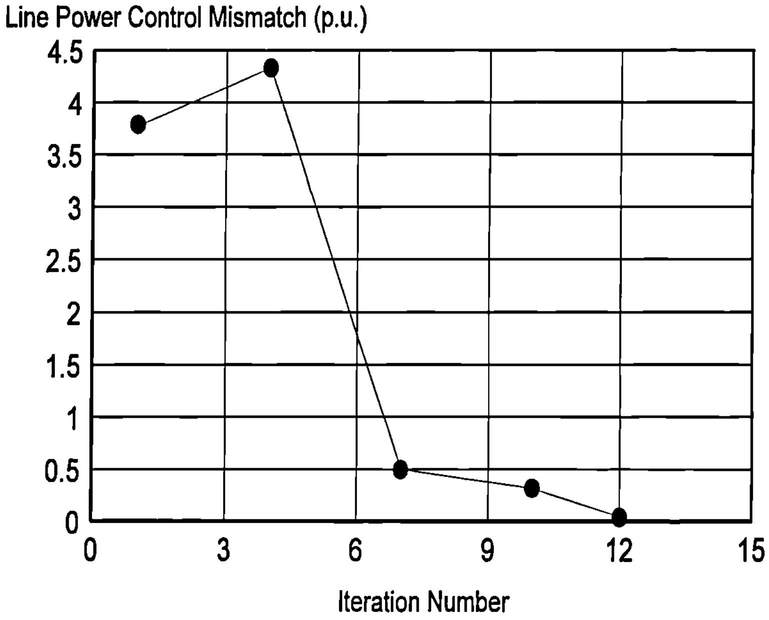


Figure 7-5 Line power mismatch vs. iteration number in PIM with one UPFC

Chapter 8

CONTROL OF UPFC
CONSTRAINED BY INTERNAL LIMITS

8.1 Introduction

On a modern power system, power transfer limits can be due to thermal, voltage or electromechanical stability transmission constraints. Studies in recent years show that FACTS devices offer a versatile alternative to conventional reinforcement methods, for the enhanced capability of power systems through the relief of these constraints.

A number of questions face the designer when considering the possible application of such UPFC devices to a system [15, 16, 17]. One of the practical questions is "what kind of control should a UPFC take when its internal limits are violated?". Reference [36] has presented a strategy to alleviate some constraints of UPFC with an objective to achieve maximum power transfer. The method of [36] used θ_{pq} to alleviate the violations of these limits, which did not consider the participation of V_{pq} and V_{sh} and thus losing some degrees of control freedom. Furthermore, when some limit is violated by a variable, it is necessary to set the violation variable at the limit value in order to achieve the highest efficiency of UPFC. In this situation, the original control performance may deteriorate and the original control objective should transform into another type, that is, the limit values of these violation variables are specified as the control objectives. This chapter further develops the Power Injection Model based UPFC control approach (PIM) proposed in the previous chapter to consider a number of internal limits imposed on the UPFC. Constrained control strategies are proposed and tested on a 28-node test system. The numerical results will illustrate the effectiveness of the proposed method.

8.2 Control of UPFC Constrained by Internal Limits

8.2.1 The Internal Limits of UPFC Device

There are five internal limits constraining the operation of a UPFC:

(1) series injection voltage magnitude (V_{pq})

$$V_{pq} \le V_{pq}^{L} \tag{8-1}$$

(2) line current through the series inverter (I_{se})

$$I_{se} = \left| \frac{\dot{V}_i + \dot{V}_{pq} - \dot{V}_j}{Z_{ij}} \right| \le I_{se}^{L} \tag{8-2}$$

(3) real power transfer between the shunt inverter and series inverter (P_{dc})

$$\left| P_{dc} \right| = \left| \mathrm{Re}\left[\dot{V}_{pq} \left(\frac{\dot{V}_i + \dot{V}_{pq} - \dot{V}_j}{Z_{ij}} \right)^{*} \right] \right| \le P_{dc}^{L} \tag{8-3}$$

(4) current through the shunt inverter (I_{sh})

$$I_{sh} = \left| \frac{\dot{V}_i - \dot{V}_{sh}}{Z_{i0}} \right| \le I_{sh}^{L} \tag{8-4}$$

(5) shunt injection voltage magnitude (V_{sh})

$$V_{sh} \le V_{sh}^{L} \tag{8-5}$$

where superscript L in each equation represents the maximum limit value of the variable.

8.2.2 Considerations of Internal Limits in Power Flow Control Methods

In general, the series injection voltage and line constraints are enforced by adjusting the scheduled levels of series P and Q. The maximum current through the series inverter is the line thermal current. While the real power transfer between the shunt inverter and series inverter is strictly an equipment rating. The shunt voltage current and voltage are constrained by the rating of the shunt inverter, which must be at least as large as the real power transfer between the two inverters. Additional capability will be required to provide the reactive current needed to regulate bus voltage. Hence, the shunt inverter current is limited by relaxing the scheduled bus voltage.

All the above limits of UPFC should be enforced in power flow calculations. A simple alternative is that these constraints checked at each iterative step in conventional power flow may be used in the UPFC constraints. If there are violations of these limits, it may slow down convergence, or more seriously, cause the solution to oscillate or even diverge. In order to alleviate these limits, the common practice is either to decrease the scheduled control objective levels or to adjust control parameters. However, this method can not be adopted in the proposed PIM because PIM can only obtain control parameters until the whole procedure of PIM converges at the final iterative step. Therefore, developing another way of handling UPFC limits in PIM is necessary.

When PIM gives the final results of power flow using UPFC control objectives, all constraints of UPFC can be checked. If the violations of these constraints occur, the control parameters of UPFC can be adjusted to avoid these limits and thus the original scheduled control objectives are impossible to achieve. The effects of the adjusted parameters of UPFC owing to their constraint violations on the power flow are evaluated through the modified power injection model of UPFC. The way of dealing with these constraints in PIM at the final step has more advantages than that of conventional way because it avoids the interference of constraints in the process of control objectives and also avoids computation oscillation or divergence.

When PIM ends with power flow results including UPFC parameters, it is quick to check whether these constraints have been violated. If not, PIM outputs with the satisfactory scheduled control objectives and the UPFC parameters within the ranges of device ratings. Otherwise, PIM will modify UPFC parameters and the associated control objectives.

8.2.3 Strategies to Handling the Constraints

The following rules are proposed to design UPFC control when the internal limits of UPFC are violated:

(1) If V_{pq} violates the constraint, fix it as its maximum value in the remaining computation process;

(2) If one of I_{se} and P_{dc} is out of the range of limit, fix it as the limit value and then solve the θ_{pq} and/or V_{pq} using the associated equations;

(3) If both I_{se} and P_{dc} limits are violated, solve the V_{pq} and/or θ_{pq} respectively at first, then choose the one which ensures both I_{se} and P_{dc} within the limits;

(4) If I_{sh} is beyond the limit while V_{sh} is within the range, relax V_i to alleviate I_{sh} and use V_i to obtain the associated reactive power injection as to achieve the new specified V_i;

(5) If the violation of V_{sh} occurs, set it as the constraint value and then use it to examine whether I_{sh} is out of the range or not. If it leads to violation of I_{sh}, repeat step (4);

(6) If I_{sh} and V_{sh} both are out of the ranges, use their maximum constraints to solve the new specified V_i.

The above rules can be mathematically implemeted by the following control strategies:

(1) Set I_{se}^{L} as control objective

Owing to the limit violation of I_{se}, the modification of θ_{pq} can be formulated from I_{se}^{L} in equation (8-2):

$$\cos(\theta_{pq}-\alpha_1)\le\frac{\cos\alpha_1}{2B_{ij}^2V_{pq}(e_i-e_j)}\left[(I_{se}^L)^2-B_{ij}^2V_{pq}^2-B_{ij}^2(e_i-e_j)^2-B_{ij}^2(f_i-f_j)^2\right] \tag{8-6}$$

$$\alpha_1=a\tan\left(\frac{f_i-f_j}{e_i-e_j}\right) \tag{8-7}$$

Based on equations (8-6) and (8-7), one method to alleviate I_{se} from its limit is to get a new θ_{pq} while keep V_{pq} constant, this has been demonstrated in reference [36]. Only is θ_{pq} used to regulate I_{se}, it may have many solutions to satisfy equation (8-6). However, in this situation, UPFC does not operate at the I_{se}^{L} and thus loses its advantage. In order to change the way of θ_{pq} which has limited capability of regulating I_{se}, V_{pq} is taken for granted to regulate I_{se} along with θ_{pq}. Therefore, the more general formulae of modifying V_{pq} and θ_{pq} are derived as follows to alleviate I_{se}:

$$\cos(\theta_{pq}-\alpha_1)=C_{se} \tag{8-8}$$

$$-B_{ij}^2V_{pq}^2-C_{se}\left|\frac{2B_{ij}^2(e_i-e_j)}{\cos\alpha_1}\right|V_{pq}+\left[(I_{se}^L)^2-B_{ij}^2(e_i-e_j)^2-B_{ij}^2(f_i-f_j)^2\right]=0 \tag{8-9}$$

$$-1\le C_{se}\le 1 \tag{8-10}$$

Here, a factor C_{se} is introduced to secure the solution of θ_{pq}, whose value can be specified within the range of [-1, 1]. C_{se} introduced here enables the UPFC to operate at the I_{se}^{L} and makes full use of its rating through both V_{pq} and θ_{pq}. So, once I_{se} is found out of the range, the control objective becomes I_{se}^{L}. Using equations(8-8)-(8-10), the modified V_{pq} and θ_{pq} change the power injections ($P_{i(inj)}$, $P_{j(inj)}$, $Q_{j(inj)}$) and thus control I_{se} towards I_{se}^{L}.

(2) Set P_{dc}^{L} as control objective

The modification of θ_{pq} can be obtained from P_{dc}^{L} due to the violation of P_{dc}:

$$P_{dc}^{L} = \left| B_{ij} V_{pq} (e_i - e_j) \frac{\sin(\theta_{pq} + \alpha_2)}{\cos\alpha_2} \right| \tag{8-11}$$

$$\alpha_2 = a\tan\left(\frac{f_j - f_i}{e_i - e_j} \right) \tag{8-12}$$

Similar to C_{se}, another factor C_{dc} is given to obtain both V_{pq} and θ_{pq} as to alleviate P_{dc}.

$$\sin(\theta_{pq} + \alpha_2) = C_{dc} \tag{8-13}$$

$$V_{pq} = \left| \frac{P_{dc}^{L} \cos\alpha_2}{C_{dc} B_{ij} (e_i - e_j)} \right| \tag{8-14}$$

$$-1 \le C_{dc} \le 1, \quad C_{dc} \ne 0.0 \tag{8-15}$$

P_{dc}^{L} will be regarded as the new control objective once P_{dc} violates its limit.

(3) Set I_{sh}^{L} as control objective

If I_{sh} violates its limit, we can relax V_i to alleviate it. For example, if it violates its upper limit, we have :

$$V_i^2 - 2f_{sh}f_i - 2e_{sh}e_i + V_{sh}^2 = \left(\frac{I_{sh}^L}{B_{i0}}\right)^2 \qquad (8\text{-}16)$$

Then V_i can be obtained from the following quadratic equation:

$$V_i^2 + (-2f_{sh}\sin\theta_i - 2e_{sh}\cos\theta_i)V_i + (V_{sh}^2 - \left(\frac{I_{sh}^L}{B_{i0}}\right)^2) = 0 \qquad (8\text{-}17)$$

$$\Delta Q_{i(inj)}^{k} = \Delta Q_{i(inj)}^{k-1} - B_{ii}\Delta e_i^k e_i^k \qquad (8\text{-}18)$$

Therefore, $Q_{i(inj)}$ is modified by the solved V_i while other injected powers ($P_{i(inj)}$,$P_{j(inj)}$, $Q_{j(inj)}$) are assumed unchanged.

8.2.4 Flow Chart of the Proposed Control Algorithm

In summary, an iterative PIM method with ability to check internal constraints and to design the associated control strategy is shown in Figure 8-1.

8.3 Numerical Results

8.3.1 The Operations of the Meshed Test System

The power flow results of two operation conditions and outages on the test system are listed in Table 8-1 .

Scenario A is a typical operating condition, which is the result of 20% increase generation in upper network based on normal generation-load pattern, leading to a big increase of power transfer across boundary A.

From Table 8-1 , it is seen that the transfer capability across boundary A is limited by violations of line thermal and busbar voltage constraints and the power sharing among the line across boundary A is unbalanced and also there is enough space left for these lines to transfer the given power without exceeding thermal limits. If the system is designed to transfer the given power across boundary A under these operating points, there are two basic ways which can be used: one is to build new transmission lines or replace the line with a new and higher thermal limit transmission line; another is to install control devices to share loads among the boundary lines, in this case, the total transfer capability of this method is determined by the sum of thermal limits of these lines and thus it enhances the system transfer capability. Therefore, UPFCs can expect to play an important role in enhancing the system in this aspect.

Except for the operation ‘Scenario A’, a number of operation conditions with line outage have presented previous chapter using the proposed PIM. In the previous chapter, PIM not only can control busbar voltage and line active power transfer effectively, but also successfully alleviate the violations of system limits and thus increase the transfer capability across boundary A. However, in order to demonstrate the adaptive control of UPFC with the constrained internal limits, this paper only focuses on its evaluation of performance of the proposed control strategy. All simulation results of next section is studied based on ‘Scenario A’ operation condition with outage of line 40-70.

8.3.2 Alleviation of Constraint Limit Violations Using the Proposed Control Strategy

As discussed in the aforementioned section, PIM has the necessary function of dealing with the constrain limits of UPFCs and differs its way of coping with them from the conventional power flow control methods. From the flow chart of PIM in Figure 8-1, it is seen that PIM only deals with their constraints of UPFCs after PIM converges at the control objectives, which avoids considering them in the process of computation of control and thus avoids unnecessary iterative modifications of UPFC power injections. Therefore, the benefit of PIM concerning UPFC limits is that PIM indirectly modifies control parameters through power injections and thus leads to constrained parameters of UPFC which fall into their limit ranges. However, it should be pointed out that this modification will destroy the original specified control objectives of interest.

Tables 8-2 ~ 8-5 present three kinds of modifications of UPFC constraints. They all begin with ideal control objectives and PIM can really do so. However, these objectives lead to UPFC limit violations, for example I_{se} of Tables 8-2 and 8-3 and P_{dc} of Table 8-4 and I_{sh} of table 8-5. In these situations, making use of relations of limit values with UPFC parameters and power injections, PIM ignores control objectives and modifies power flow control towards the satisfactory parameters within their limits. All tables are investigated under 'Scenario A' with one UPFC installed along line 90-60 and with different initial control objectives, which yield violations of I_{se}, P_{dc} and I_{sh}.

In Tables 8-2 and 8-3, I_{se} violates its limit according to the control objective and thus PIM fixes I_{se} at the I_{se}^L and obtains the modified V_{pq} and/or θ_{pq} and the associated power injection values. After PIM gets new power flow results using these modified power injection control, it can be seen that violation of I_{se} can be efficiently alleviated with 3~4 iterative solutions. In fact, the final V_{pq} and θ_{pq} have been treated as the control value to modify power injections and thus it achieves alleviation of I_{se} limit, which can be seen that the modified $\theta_{pq}= 146.06^0$ is the same as the final result of phase of V_{pq} of Table 8-2. In Table 8-2, only θ_{pq} is used to modify power injections while V_{pq} remains nearly unchanged. In this typical case, C_{se}=0.1929. However, under the same case, when C_{se} is chosen to be 0.92, V_{pq} and θ_{pq} both co-operate to modify power injections to achieve the same goal, which is shown in Table 8-3. Compared to Table 8-2, results of Table 8-3 have one more control degree of freedom to achieve the same objective. This shows that the proposed general control equations has more advantages applicable to alleviation of I_{se} within I_{se}^L. Similar to Table 8-3, the violation of P_{dc} limit is alleviated through the modified V_{pq} and θ_{pq} and thus the associated power injections, whose performance is shown in Table 8-4. For both I_{se} and P_{dc} cases, three power injections ($P_{i(inj)}$, $P_{j(inj)}$, $Q_{j(inj)}$) relating to modified V_{pq} and θ_{pq} are adjusted to achieve I_{se} and P_{dc} equal to their limits while $Q_{i(inj)}$ is kept unchanged.

In Table 8-5, V_{90} is relaxed from 1.0096 p.u. of I_{sh} violating limit to 1.0032 p.u. without violation. Here, V_{90} is first obtained from equation specified I_{sh}^{L}, and then used to modify $Q_{i(inj)}$ while keeps power injections ($P_{i(inj)}$, $P_{j(inj)}$, $Q_{j(inj)}$) unchanged. The modified $Q_{i(inj)}$ is obtained through busbar voltage--reactive power injection controller equation. At last, I_{sh} violation has been alleviated through relaxing V_{90}.

Other two methods of handling V_{pq} and V_{sh} violations are easily incorporated in PIM because they can be directly used to modify power injections and thus alleviate violations. All these procedures of dealing with limits are formed as one necessary part of the proposed PIM.

A large set of test studies clearly demonstrate that the proposed PIM method provides a novel and efficient way of dealing with UPFC limits in terms of power injections. The modified power injections indirectly represent the effects of the new control objectives due to violations of internal limits on the system and thus regulate the UPFC to operate at its internal limit. Although the proposed method is only implemented in the PIM algorithm, it is also suitable for other UPFC power flow control methods.

8.4 Summary

This chapter has developed a Power Injection Model based UPFC control approach to consider a number of internal limits imposed on the UPFC, including series injection voltage magnitude, line current through the series inverter, real power transfer between the shunt inverter and series inverter, shunt side current and shunt injection voltage magnitude. The proposed control strategies can co-ordinate the available control variables to achieve an efficient usage of the UPFC when it is constrained by the internal limits. Test results on the meshed test system have illustrated the effectiveness of the proposed method.

Table 8-1 Power flow results with contingence without UPFC

	operating condition	outage line	transfer capability across A boundary	lowest voltage (p.u)	violations of line thermal limits and voltage limits
case	Scenario A	line 40-70	13154MW	V_{50}=0.95764	line 50-60 108.4% line 60-90 108.49%

Table 8-2 Results of UPFC with constraint limit check of I_{se} (C_{se}=0.1929)

	results of I_{se} limit violation I_{se}^L	results of alleviating I_{se} violation
original power flow results	V_{90}= 0.96884 P_{90-60}= -20.786	
control cbjectives	V_{90}= 0.99 P_{90-60}= -23.00	
actual power flow results	V_{90}= 0.9895 P_{90-60}= -22.966	V_{90}= 0.98649 P_{90-60}= -22.20
power injection values	$P_{i(inj)}$= -4.5311 $Q_{i(inj)}$ = 4.8221 $P_{j(inj)}$ = 4.5311 $Q_{j(inj)}$ = -4.0	$P_{i(inj)}$ = -2.5712 $Q_{i(inj)}$ = 4.8211 $P_{j(inj)}$ = 2.5712 $Q_{j(inj)}$ = -5.4696
V_{pq} θ_{pq}	V_{pq}= 0.0816 θ_{pq}= 123.04^0	V_{pq} = 0.0823 θ_{pq} = 146.07^0
V_{sh} θ_{sh}	V_{sh}= 0.9909 θ_{sh}= -28.94^0	V_{sh}= 0.9814 θ_{sh}= -27.47^0
I_{se}	I_{se}=27.4885	I_{se}=24.83
I_{se}^L	I_{se}^L=25.0	
iteration	3	
modified θ_{pq}	θ_{pq}= 146.06^0	

Table 8-3 Results of UPFC with constraint limit check of I_{se} (C_{se}=0.92)

	results of I_{se} limit violation I_{se}^L	results of alleviateing I_{se} violation
original power flow results	V_{90}= 0.96884 $P_{90\text{-}60}$= -20.786	
control objectives	V_{90}= 0.99 $P_{90\text{-}60}$= -23.00	
actual power flow results	V_{90}= 0.9895 $P_{90\text{-}60}$= -22.966	V_{90}= 0.98929 $P_{90\text{-}60}$= -22.191
power injection values	$P_{i(inj)}$= -4.5311 $Q_{i(inj)}$ = 4.8221 $P_{j(inj)}$ = 4.5311 $Q_{j(inj)}$ = -4.0	$P_{i(inj)}$ = -2.5481 $Q_{i(inj)}$ = 4.8211 $P_{j(inj)}$ = 2.5481 $Q_{j(inj)}$ = -0.4570
V_{pq} θ_{pq}	V_{pq}= 0.0816 θ_{pq}= 123.04^0	V_{pq} = 0.0349 θ_{pq} = 90.024^0
V_{sh} θ_{sh}	V_{sh}= 0.9909 θ_{sh}= -28.94^0	V_{sh}= 1.008 θ_{sh}= -26.759^0
I_{se}	I_{se}=27.4885	I_{se}=24.97
I_{se}^L	I_{se}^L=25.0	
C_{se}	0.92	
iteration	4	
modified V_{pq}	V_{pq}=0.0349	
modified θ_{pq}	θ_{pq}= 90.157^0	

Table 8-4 Results of UPFC with constraint limit check of P_{dc} (C_{dc}=1.0)

	results of P_{dc} limit violation P_{dc}^{L}	results of alleviating P_{dc} violation
original power flow results	V_{90}= 0.96884 P_{90-60} = -20.786	
control objectives	V_{90}= 0.99 P_{90-60}= -23.0	
actual power flow results	V_{90}= 0.9895 P_{90-60}= -22.966	V_{90}= 0.99166 P_{90-60}= -22.479
power injection values	$P_{i(inj)}$ = -4.5311 $Q_{i(inj)}$ = 4.8211 $P_{j(inj)}$ = 4.5311 $Q_{j(inj)}$ = -4.0	$P_{i(inj)}$ = -3.2259 $Q_{i(inj)}$ = 4.8211 $P_{j(inj)}$ = 3.2259 $Q_{j(inj)}$ = 5.2233
V_{pq} θ_{pq}	V_{pq}= 0.0816 θ_{pq}= 123.04^{0}	V_{pq}= 0.0829 θ_{pq}= 23.059^{0}
V_{sh} θ_{sh}	V_{sh}= 0.9909 θ_{sh}= -27.94^{0}	V_{sh}= 1.0353 θ_{sh}= -26.31^{0}
P_{dc}	P_{dc}=1.6023	P_{dc}=1.305
P_{dc}^{L}	P_{dc}^{L}=1.3	
C_{dc}	C_{dc}=1.0	
iteration	2	
modified V_{pq}	V_{pq}=0.0829	
modified θ_{pq}	θ_{pq}=23.096^{0}	

Table 8-5 Results of UPFC with constraint limit check of I_{sh}

	results of I_{sh} limit violation I_{sh}^{L}	results of alleviating I_{sh} violation
original power flow results	V_{90}= 0.96884 P_{90-60}= -20.786	
control objectives	V_{90}= 1.01 P_{90-60}= -23.00	
actual power flow results	V_{90}= 1.0096 P_{90-60}= -22.974	V_{90}= 1.00245 P_{90-60}= -22.970
power injection values	$P_{i(inj)}$= -3.8474 $Q_{i(inj)}$ = 10.6426 $P_{j(inj)}$ = 3.8474 $Q_{j(inj)}$ = -4.0	$P_{i(inj)}$ = -3.8474 $Q_{i(inj)}$ = 9.1764 $P_{j(inj)}$ = 3.8474 $Q_{j(inj)}$ = -4.0
V_{pq} θ_{pq}	V_{pq}= 0.0752 θ_{pq}= 127.43^0	V_{pq} = 0.0753 θ_{pq} = 127.34^0
V_{sh} θ_{sh}	V_{sh}= 1.0377 θ_{sh}= -27.49^0	V_{sh}= 1.0236 θ_{sh}= -27.67^0
I_{sh}	I_{sh}=5.8119	I_{sh}=4.482
I_{sh}^{L}	I_{sh}^{L}=4.5	
iteration	3	
modified V_{90}	V_{90}=1.0032	
modified $Q_{i(inj)}$	$Q_{i(inj)}$ =9.1764	

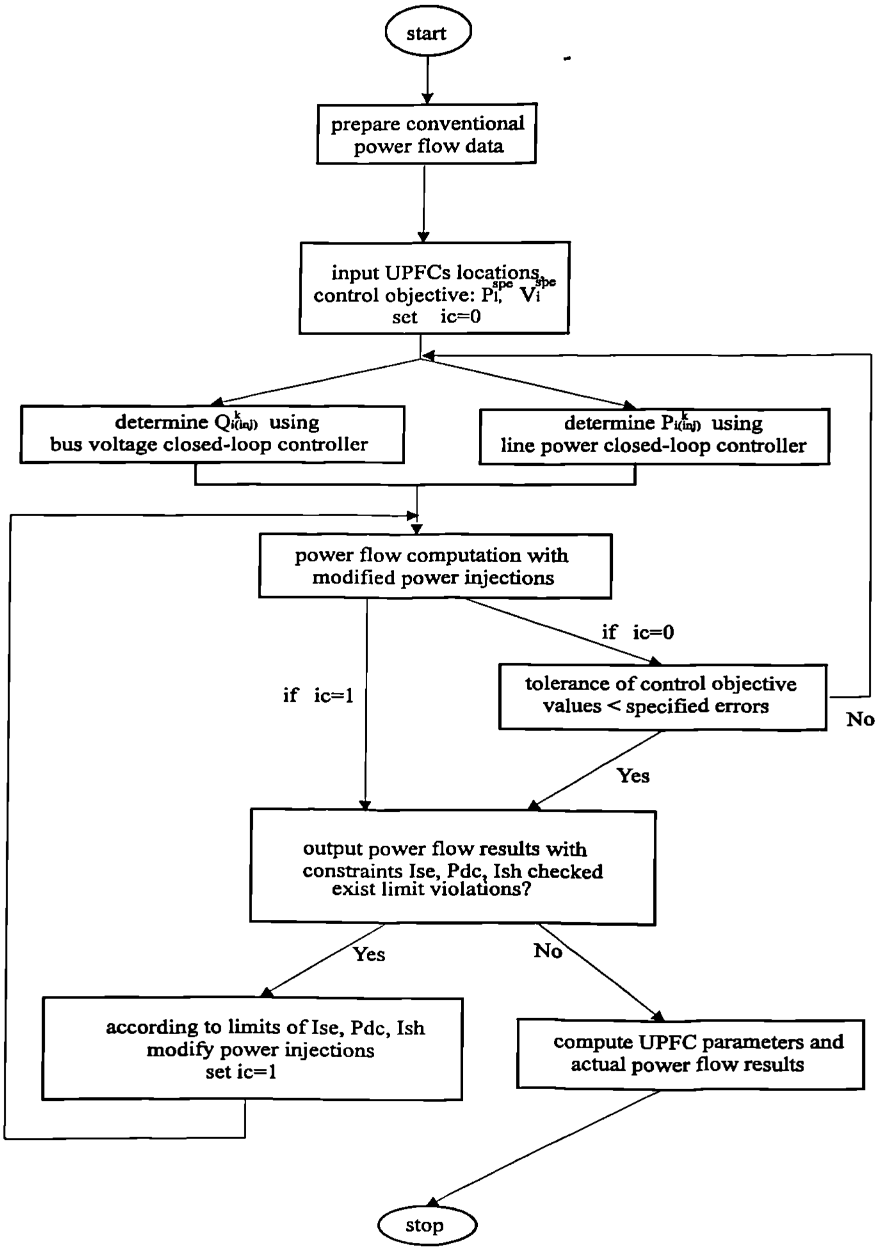


Figure 8-1 Flow chart of the proposed PIM method

Chapter 9

CONCLUSIONS AND FUTURE WORK

The thesis is concentrated on modelling and control of the UPFC. It concentrates on algorithmic and analytical methodology. The overall aim of the work is to provide a systematic method to investigate the impacts of UPFC on the performance of transmission systems.

Some models and algorithms have been proposed in the literature for modelling and control of the UPFC. Most appear to have limited practice, and currently engineers depend largely on commercial software to evaluate impacts of the UPFCs on transmission systems. However, most of these commercial software do not directly provide facilities of implementing the UPFC model. Although they have functions of user-defined model for users to set up the UPFC model, structures of algorithms of these software may limit themselves to realise some functions of the UPFC. Any new development in the modelling and control of UPFC should take the following requirements into full considerations;

(1) Modelling of the UPFC

Modelling of the UPFC is a fundamental step for any UPFC related studies. The developed models of the UPFC should (i) cover three main states of power system operations, (ii) contain the main features of the real-world UPFC, (iii) be consistent in terms of viewpoint of the system, (iv) be flexible and readily changeable to suit the associated algorithms adopted.

(2) Algorithms to implement the UPFC models

The developed algorithms should be thoroughly investigated ranging from algorithm convergence, computing time as well as whether they are suitable for control strategies to be incorporated. This is due to the following peculiarities existing in the UPFC: (i) power transfer between two inverters; (ii) wide regulation range of control parameters; (iii) non-linear multivariable control and (iv) stressed conditions of the system with UPFC. All these require to develop robust yet flexible algorithms for transmission systems with embeded UPFCs in open-loop and closed-loop forms.

(3) Strategy to control the UPFCs

Control is the key of the UPFC. The concept of the UPFC is that it has ability to concurrently control voltage and transmission line power flow. Therefore, designing control strategies for the UPFC under different states is necessary to realise its functions. The following factors affecting control strategies of the UPFC need to be considered: (i) Clarify control objectives under different states. For different states, the system may produce various unexpected phenomena, in which the UPFC is demanded to eliminate. (ii) Clarify central and local schemes. As is well known, the control objective of the UPFC can either be global or local and thus leads to different methods. (iii) Choose right input signals to control schemes. As the control objective is clarified into global, local and different states, it is very important to understand what kind of signals can be obtained and used to achieve the defined objective. (iv) Adopt advanced control technology. With rapid development of modern control theory, the UPFC has more wide choices for its control scheme.

Most of the above requirements have been met by models, algorithms and approaches proposed in this thesis with particular emphasis on electromagnetic transient state and steady-state analysis.

9.1 Comparison Studies of Modelling and Control Methodology

Before carrying out any new development in modelling and control of the UPFC, one is required to investigate and compare all the technologies already applied on the UPFC and/or other control devices of the same category so as to come to the conclusion which kind of methods should be adopted. In this respect, development of FACTS controllers associated with power electronic devices has been systematically reviewed in the thesis. Furthermore, issues of applying the UPFC in transmission systems have been analysed. In particular, the following general aspects of FACTS related studies have been reviewed:

- Development of power electronics devices
- FACTS equipment classifications and main features
- Issues with the applications of UPFCs in transmission systems
- Various structure and models for UPFC
- Special features of EMTP simulation tool for studying UPFC
- Optimal multiplier power flow method with its advanced convergence characteristics
- Comparison of power flow control methods for implementing control devices

9.2 Modelling and Control of the UPFC under the Electromagnetic Transient State

The model and control of the UPFC under the electromagnetic transient state provides users a deep insight into every detail of the UPFC physical circuit. From this viewpoint, one can better understand what the UPFC can do and how it does. Although the inventor of the UPFC has mentioned the possibility of the PWM control method employing by the UPFC's internal control, there has no any literature involving this kind of work before we finish preliminary studies on this aspect. In the thesis, a prototype model for the PWM based UPFC of the electromagnetic transient state has been set up by using its detailed physical power electronic device as well as its internal closed-loop controller. The problems encountered in the process of building such a model and the way of EMTP handling them have been discussed. Most of the factors affecting the model and control of the UPFC have been investigated including (i) harmonics generation and filters effects; (ii) SPWM based switching signal generator; (iii) the open-loop and closed-loop control. This prototype model has completely realised the functions promised by the inventor of the UPFC and can be extended to many fields of the UPFC research such as protection design, stability analysis and fault computation.

9.3 Modelling of Steady-State UPFC and Its Implementation in Optimal Multiplier Power Flow

The most important step to apply the UPFC is to evaluate its impacts on transmission systems of interest. As the UPFC was proposed to control power flow, it is nature for engineers to start from the steady-state UPFC. The steady-state UPFC model can be of various forms but it must match the concept and provide all functions of the UPFC. A general UPFC model purely derived from the concept of the UPFC may ignore links between the electromagnetic transient state and the electromechanical transient state. In the thesis, a two voltage source model for the steady-state has been set up for the UPFC in terms of rectangular forms in order to suit for the adopted optimal multiplier power flow algorithm. This model can take many practical factors into considerations: (i) the way of modulating the two voltage sources by SPWM; (ii) internal relations between both voltage sources; (iii) five internal constraints imposed by the complicated physical limits of the UPFC. The model realises functions of voltage support and power flow control in the system without losing reality. However, this form of the UPFC cannot be directly implemented in conventional power flow methods and it should be transformed. The main reason for this is that conventional power flow methods cannot deal with the additional series components of the UPFC or other similar control devices. Therefore, a form in terms of power injection model of the steady-state UPFC suitable for implementation in optimal multiplier power flow computation method has been adopted. The reason for choosing optimal multiplier power flow algorithm is its robust and better convergence. The whole process of enhancing optimal multiplier algorithm by the proposed UPFC model has been demonstrated. Simulation results have been obtained on IEEE benchmark model system and a practical system to explain benefits of this model to the studied systems. Furthermore, one can readily identify their deficiencies especially using the popular user defined model method through comparing the way of dealing with the UPFC.

9.4 Maximum Regulating Capability of UPFC

Once the steady-state model of the UPFC has been implemented in optimal multiplier power flow algorithm, it is then to evaluate its impacts on the performance of the system or vice versa. One of the important issues on such evaluations is how much the controllable parameters of the UPFC can be regulated to push the system to achieve the boundary of feasibility region of steady-state power flow solution. The question is raised because it is possible to have cases where a feasibility limit is reached before a thermal limit or other steady-state security limits. Therefore, answers to this question can give operators and planners information about the maximum regulating capability of the UPFC and the system critical points. In the thesis, an indicator-- the optimal multiplier μ in optimal multiplier power flow algorithm-- has been chosen to predict predicted boundary point of the feasible region associated with singularity of Jacobian matrix in order to determine the maximum regulating capability of the UPFC. This method overcomes the difficulty of estimating boundary points of feasibility region in other literature, in which they often spend much more time or efforts. A step-by-step procedure has been proposed based on this indicator. Used such a procedure, three dimensional images describing the ranges have been obtained on a IEEE-30 model system and the results have been compared with minimum singular value decomposition method. The regulating capabilities of the UPFC under different parameter patterns are also presented.

9.5 Closed-Loop Control of Steady-State UPFCs

The UPFC offers new horizons in terms of power system control, with the potential to independently control up to three power system parameters, for instance bus voltage, line active power and line reactive power. The difficulties of forming closed-loop control strategies for the steady-state UPFCs lie on the different objective for individual control parameter while there are coupling relations among these parameters. Although the Automatic adjustment method may solve this multi-parameter control problems, it still leaves some problems unsolved: (i) unfit assumptions of initial conditions may leads to divergence of the procedure; (ii) it cannot cover whole 360 degree range of the UPFC control capability because it starts from one point to search for the solution based on sensitivity factors; (iii) it needs to be reconstructed whole Jacobian matrix of the algorithm which is not an easy task for existing commercial software. Corresponding to these problems, a novel method to overcome them has been proposed in the thesis. The method is called PIM, power injection model based control strategy algorithm, in which an overall UPFC control strategy is envisaged which involves local UPFC controllers to enable the UPFC to achieve the required set-points. The control strategies, fully making use of physical characteristics of power injection model of the UPFC, are designed by: (i) closed-loop voltage control strategy by reactive power injection (ii) closed-loop line transfer active power control strategy by active power injections. The assumptions, algorithmic process, convergence, performance and impacts of the algorithm on the system have been investigated in great details and tested on a meshed system derived from a large-scale practical system. One of additional benefits derived from this method is that finally results can directly give control parameters as well as ratings and sizes of the UPFCs. While the great potentials of this method may lie on that it can be incorporated into existing commercial software with the least efforts while it doesn't destroy their original structures and codes.

9.6 Control of UPFC Constrained by Its Internal Limits

The model of the steady-state UPFC should have constraints in order to reflect the practical physical circuit. In the thesis, five internal limits of the UPFC physical model have been derived as the constraints to its performances. These limits are: (i) series injection voltage magnitude (V_{pq}); (ii) line current through the series inverter (I_{se}); (iii) real power transfer between the shunt inverter and series inverter (P_{dc}); (iv) current through the shunt inverter (I_{sh}); (v) shunt injection voltage magnitude (V_{sh}). Apparently, the steady-state model and control of the UPFC will be much more complicated with these internal limits. In Automatic Adjustment method, these limits are dealt with in the end of every iteration which leads to more iterations and distorted sensitivity information of correcting variables for next iteration step. In the thesis, a complete set of control rules considering these limits in PIM has been reconstructed to form the basis of optimal UPFC control strategies for its steady-state local control. These limits have been treated as new control objectives when they are violated by original control strategies of PIM. The UPFC's parameters are then modified to limit these constraints in order to pull the violating limits within their ranges. This control set integrates PIM algorithm as a complete controller for the steady-state UPFCs. Various simulation studies have been conducted under this procedure and they have been validated on a meshed system. The studies results are very practical and encouraging.

In conclusion, the work in this thesis provides some fundamental models and methods to effectively investigate the UPFC and evaluate its impacts on transmission systems. They have been tested by some practical system data, which has proved them to be very effective and practical. The system planners and operators can use these theories and tools to solve problems which they will certainly encounter when they apply UPFCs.

9.7 Future Work

Some fundamental development of modelling and control of the UPFC has been made and the results of study have confirmed that the approaches proposed in this thesis are well suited to practical system planning and operations. However, as being a new technology, development, research and application of the UPFC are just in an infant period and some important issues are still open for researchers to do further work so as to best apply the UPFC in transmission systems.

The following are some suggestions for further research in the UPFC related applications.

9.7.1 The Electromagnetic Transient State

For modelling, simulation and control of the electromagnetic transient state UPFC, it is worth using the set-up prototype model of the UPFC to continue research in such fields as:

(1) Simulations of faults on the system or within the internals of inverter bridges of the UPFC. Both are important to evaluating the performance of the UPFC because faults within or outside the UPFC may lead to distortions of its waveform output and thus worsening the system operational quality. The design of internal control of the UPFC may need to take this factor into consideration.

(2) Design of optimal structure and parameters for the UPFC. The real UPFC may be constructed based on multi-layer arrangements of GTO VSI bridges which often depends on the ratings of the GTO power. So, this is a sufficient reason to investigate different arrangements and design optimal various parameters of filters, snubber circuits, dc link capacitors and transformers.

(3) Selections of various modulation methods. There are many advanced modulation methods for switching control of the VSI circuits, which are suited for different control objectives. The UPFC may benefit from them to achieve better output waveforms and less percentages of

harmonics. It is also valuable to respectively experience different modulation methods to the series and the shunt VSI part of UPFC.

(4) Evaluation of losses in the UPFC. As the GTO-based VSI adopts the high frequency pulse-width-modulation method and thus increasing losses of the circuits, it is important to develop methods to accurately estimate these losses, which associate with different arrangements of the UPFC and the modulation methods as well as the switching frequency of the used thyristor.

Furthermore, various control schemes can be designed to replace the proposed PID internal controllers in the thesis to achieve more flexible and robust control objectives. It should be pointed out that every aspect described above can be well done through modifications of the proposed UPFC prototype model.

9.7.2 The Steady-State

The future work for the steady-state UPFC should focus on designing of the global control strategy and optimal rating determinations and identifications of the optimal UPFC locations. These problems are expected to be solved by employing 'Optimal Power Flow Method' because this method can flexibly construct control objectives which are 'optimal locations' or 'minimum ratings' or 'transfer powers across some boundary' and so on. The model of the UPFC should contain various equation expressions as well as five internal limits. However, having the weak convergence, the existing optimal power flow methods need much efforts to be made to achieve their practical applications. The widely accepted method is Newton-method optimal power flow and the future may involve Interior Point (IP) method. With the development of electricity market, UPFC will play an important role in open access systems. However, research of how to define its role and to determine its 'spot price' contributed to electricity prices is still untouched, which will be the determined factor whether the UPFC should be applied in transmission systems in the near future.

9.7.3 The Electromechanical State and System Stability

Although the UPFC was proposed for control of power flow transmission under steady-state, it can also enhance the system transient stability. The ability provided by the UPFC covers three aspects of this problem: (i) Provide sufficient damping for small-signal stability; (ii) Decrease oscillations under large disturbances. (iii) Have abilities to enhance voltage stability. Therefore, the practical applications of the UPFC call for these research in order to fully make use of the UPFC. Some problems existing in this aspect have been discussed in great details in Chapter 3. Here, only some key points are summarised up as follows:

(1) Modelling

The model of the UPFC under transient state can be regarded as the same as the steady-state phasor model. However, this model is not robust enough and it should consider the internal response time of the UPFC such as switching instants of both inverter voltage sources as well as PWM strategies. Furthermore, if unbalanced conditions of the UPFC operation are taken into consideration, it is better to use three-phase model. For small-signal stability, it is often linearised.

(2) Simulation method

The conventional time-domain simulation method may not be the best choice for the UPFC. One may need to develop new simulation methods to cope with some different features of the UPFC such as circuit imbalance, waveform distortion and non-linearity. The simulation methods may contain multi-rate algorithm, user-defined model, integration with the electromagnetic transient simulations as well as the expression of the model in terms of three-phase form.

(3) Design of the control strategy

The three aspects of designing control strategies for the UPFC are: (i) determination of the control objective; (ii) the input to the controller is from global or local signals; (iii) co-ordinations of the UPFCs with other FACTS or other control devices should be considered.

Based on above three aspects, designs of control strategies are then adopted various advanced control theories. Analysis of eigenvalue method provides a powerful tool to aid for designing, which can also be used to identify damping provided by the UPFC and locations of the UPFCs in the system.

(4) Ways of enhancing voltage stability

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance, increase in load, or system change causes voltage to drop quickly or drift downward, and operators and automatic system controls fail to halt the decay. In some extreme cases, the continuous decay would cause voltage collapse. In the process of voltage collapse, a significant part of the system suffers from very low voltage profile. It is in this process that the UPFC is expected to quickly supply sufficient reactive power in order to support system voltages. Although voltage instability is also of transient process, its operation mechanism is different from that of the electromechanical transient process. Therefore, when the UPFC is employed to enhance voltage stability, its control objectives, control strategies should be determined from viewpoint of voltage stability. Some important concepts should be helpful for designing of control strategies, such as: voltage stability margin, voltage collapse point, weak buses and critical boundaries of voltage stability and loadability. Dynamic modelling of the UPFC under voltage stability is very important, which may be addressed by employing Bifurcation Method.

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APPENDIX A: POWER FLOW DATA FORMAT

- Transmission Line Data Format

| *bus number* | *line number* |

| *type* | *bus name* | *bus name* | *G* | *B* | *C or ratio of transformer* | *G0* | *B0* | *C0* |

- Generator and Load Pattern Format

| *generator number* | *load number* | *PV bus number* | *Vθ bus name* | *voltage of Vθ bus* | *factor of load* | *factor of load* | *initial voltage of flat start* |

| *generator type* | *generator bus name* | *active power output* | *reactive power output (maximum)* |

| *generator type* | *generator bus name* | *active power output* | *maximum reactive power output* | *minimum reactive power output* |

| *load bus name* | *active power load* | *reactive power load* |

| *PV bus name* | *pre-specified voltage of PV bus* |

- Voltage Limits

| *bus number* |

| *bus number* | *bus name* | *average voltage* | *upper limit of voltage* | *lower limit of voltage* |

- Transmission Line Thermal Limits

| *line number* |

| *bus name* | *bus name* | *lower limit of line thermal limit* | *upper limit of line thermal limit* |

APPENDIX B: IEEE 30-BUS SYSTEM DATA

Transmission Line Parameters

```
  30  43
1  1  2  .01920  .05750  .05280  .00000  .00000  .00000
1  1  3  .04520  .18520  .04080  .00000  .00000  .00000
1  2  4  .05700  .17370  .03680  .00000  .00000  .00000
1  3  4  .01320  .03790  .00840  .00000  .00000  .00000
1  2  5  .04720  .19830  .04180  .00000  .00000  .00000
1  2  6  .05810  .17630  .03740  .00000  .00000  .00000
1  4  6  .01190  .04140  .00900  .00000  .00000  .00000
1  5  7  .04600  .11600  .02040  .00000  .00000  .00000
1  6  7  .02670  .08200  .01700  .00000  .00000  .00000
1  6  8  .01200  .04200  .00900  .00000  .00000  .00000
2  9  6 .00000  .20800 1.01550  .00000  .00000  .00000
2  6 10 .00000  .55600  .96290  .00000  .00000  .00000
1  9 11 .00000  .20800  .00000  .00000  .00000  .00000
1  9 10 .00000  .11000  .00000  .00000  .00000  .00000
2 12  4 .00000  .25600 1.01290  .00000  .00000  .00000
1 12 13 .00000  .14000  .00000  .00000  .00000  .00000
1 12 14 .12310  .25590  .00000  .00000  .00000  .00000
1 12 15 .06620  .13040  .00000  .00000  .00000  .00000
1 12 16 .09450  .19870  .00000  .00000  .00000  .00000
1 14 15 .22100  .19870  .00000  .00000  .00000  .00000
1 16 17 .08240  .19320  .00000  .00000  .00000  .00000
1 15 18 .10700  .21850  .00000  .00000  .00000  .00000
1 18 19 .06390  .12920  .00000  .00000  .00000  .00000
1 19 20 .03400  .06800  .00000  .00000  .00000  .00000
1 10 20 .09360  .20900  .00000  .00000  .00000  .00000
1 10 17 .03240  .08450  .00000  .00000  .00000  .00000
1 10 21 .03480  .07490  .00000  .00000  .00000  .00000
1 10 22 .07270  .14990  .00000  .00000  .00000  .00000
1 21 22 .01160  .02360  .00000  .00000  .00000  .00000
1 15 23 .10000  .20200  .00000  .00000  .00000  .00000
1 22 24 .11500  .17900  .00000  .00000  .00000  .00000
1 23 24 .13200  .27000  .00000  .00000  .00000  .00000
1 24 25 .18850  .32920  .00000  .00000  .00000  .00000
1 25 26 .25540  .38000  .00000  .00000  .00000  .00000
1 25 27 .10930  .20870  .00000  .00000  .00000  .00000
2 28 27 .00000  .39600  .95810  .00000  .00000  .00000
1 27 29 .21980  .41530  .00000  .00000  .00000  .00000
1 27 30 .32020  .60270  .00000  .00000  .00000  .00000
1 29 30 .23990  .45330  .00000  .00000  .00000  .00000
1  8 28 .06360  .20000  .04280  .00000  .00000  .00000
1  6 28 .01690  .05990  .01300  .00000  .00000  .00000
4 10  0 .00000 -5.26315  .00000  .00000  .00000  .00000
4 24  0 .00000 -25.00000 .00000  .00000  .00000  .00000
```

Generator and Load Pattern

```
  6  21   5   1  1.0500   .0000   .0000  1.0000
1  1  2.0000  2.0000
1  2   .5756  1.0000
1  5   .2456  1.0000
1  8    .3500   .5000
1 11    .1793   .4000
```

```
1  13   .1691   .3000
 2   .2170   .1270
 3   .0240   .0120
 4   .0760   .0160
 5   .9420   .1900
 7   .2280   .1090
 8   .3000   .3000
10   .0580   .0200
12   .1120   .0750
14   .0620   .0160
15   .0820   .0250
16   .0350   .0180
17   .0900   .0580
18   .0320   .0090
19   .0950   .0340
20   .0220   .0070
21   .1750   .1120
23   .0320   .0160
24   .0870   .0670
26   .0350   .0230
29   .0240   .0090
30   .1060   .0190
 2.0000   1.0338
 5.0000   1.0058
 8.0000   1.0230
11.0000   1.0913
13.0000   1.0883
```

APPENDIX C: THE MESHED NETWORK DATA

Transmission Line Parameters

```
  28  69
2  10  11  .00000  .00326 1.01650  .00000  .00000  .00000
1  10  20  .00241  .02410  .00000  .00000  .00000  .00000
1  10  20  .00482  .04820  .00000  .00000  .00000  .00000
1  10  30  .00531  .05310  .00000  .00000  .00000  .00000
1  10  30  .00531  .05310  .00000  .00000  .00000  .00000
1  20  22  .00000  .01667  .00000  .00000  .00000  .00000
1  20  30  .00465  .04650  .00000  .00000  .00000  .00000
1  20  30  .00465  .04650  .00000  .00000  .00000  .00000
1  20  40  .00342  .03420  .00000  .00000  .00000  .00000
1  20  40  .00342  .03420  .00000  .00000  .00000  .00000
2  30  31  .00000  .00387 1.02400  .00000  .00000  .00000
1  30  60  .00249  .02490  .00000  .00000  .00000  .00000
1  30  60  .00249  .02490  .00000  .00000  .00000  .00000
1  30  60  .00249  .02490  .00000  .00000  .00000  .00000
1  30  60  .00249  .02490  .00000  .00000  .00000  .00000
2  40  41  .00000  .00179 1.04150  .00000  .00000  .00000
1  40  50  .00254  .02540  .00000  .00000  .00000  .00000
1  40  60  .00044  .00440  .00000  .00000  .00000  .00000
1  40  70  .00299  .02990  .00000  .00000  .00000  .00000
1  40  70  .00299  .02990  .00000  .00000  .00000  .00000
1  40  70  .00299  .02990  .00000  .00000  .00000  .00000
1  50  60  .00208  .02080  .00000  .00000  .00000  .00000
1  50  70  .00179  .01790  .00000  .00000  .00000  .00000
2  60  61  .00000  .00144 1.06250  .00000  .00000  .00000
1  60  90  .00466  .04660  .00000  .00000  .00000  .00000
1  60  90  .00898  .08980  .00000  .00000  .00000  .00000
1  60  90  .00138  .01380  .00000  .00000  .00000  .00000
1  60 100  .00239  .02390  .00000  .00000  .00000  .00000
1  60 100  .00239  .02390  .00000  .00000  .00000  .00000
1  60 120  .00492  .04920  .00000  .00000  .00000  .00000
2  70  71  .00000  .00604 1.11350  .00000  .00000  .00000
1  70  72  .00000  .00595  .00000  .00000  .00000  .00000
1  70  80  .00106  .01060  .00000  .00000  .00000  .00000
1  70 110  .00198  .01980  .00000  .00000  .00000  .00000
1  70 110  .00198  .01980  .00000  .00000  .00000  .00000
2  80  81  .00000  .00899 1.07850  .00000  .00000  .00000
1  80  90  .00119  .01190  .00000  .00000  .00000  .00000
1  80 100  .00156  .01560  .00000  .00000  .00000  .00000
1  80 120  .00290  .02900  .00000  .00000  .00000  .00000
1  80 120  .00290  .02900  .00000  .00000  .00000  .00000
2  90  91  .00000  .00929 1.07700  .00000  .00000  .00000
1  90 120  .00386  .03860  .00000  .00000  .00000  .00000
1  90 120  .00386  .03860  .00000  .00000  .00000  .00000
2 100  10  .00000  .00521 1.08700  .00000  .00000  .00000
1 100 120  .00387  .03870  .00000  .00000  .00000  .00000
1 100 120  .00387  .03870  .00000  .00000  .00000  .00000
1 100 120  .00387  .03870  .00000  .00000  .00000  .00000
2 110 111  .00000  .00301 1.01200  .00000  .00000  .00000
1 110 112  .00000  .02778  .00000  .00000  .00000  .00000
1 110 120  .00090  .00903  .00000  .00000  .00000  .00000
1 110 130  .00254  .02540  .00000  .00000  .00000  .00000
1 110 130  .00254  .02540  .00000  .00000  .00000  .00000
```

```
 2 120  121 .00000   .00199  1.06550  .00000  .00000  .00000
 1 120  122 .00000   .00298   .00000  .00000  .00000  .00000
 1 120  130 .00735   .07350   .00000  .00000  .00000  .00000
 1 120  130 .00735   .07350   .00000  .00000  .00000  .00000
 1 130  132 .00000   .00758   .00000  .00000  .00000  .00000
 4  10   0  .00000  -.06024   .00000  .00000  .00000  .00000
 4  20   0  .00000  -.29412   .00000  .00000  .00000  .00000
 4  30   0  .00000  -.16393   .00000  .00000  .00000  .00000
 4  40   0  .00000  -.03155   .00000  .00000  .00000  .00000
 4  60   0  .00000  -.04082   .00000  .00000  .00000  .00000
 4  70   0  .00000  -.03817   .00000  .00000  .00000  .00000
 4  80   0  .00000  -.50000   .00000  .00000  .00000  .00000
 4  90   0  .00000  -.47619   .00000  .00000  .00000  .00000
 4 100   0  .00000  -.34483   .00000  .00000  .00000  .00000
 4 110   0  .00000  -.03906   .00000  .00000  .00000  .00000
 4 120   0  .00000  -.00869   .00000  .00000  .00000  .00000
 4 130   0  .00000  -.06578   .00000  .00000  .00000  .00000
```

Generator and Load Pattern

```
  15   13   14   61   1.0000   .0000    .0000  1.0000
 1  11  46.1000   29.1000 -16.5000
 1  22    .0000    3.0000  -1.5000
 1  31  38.7000   26.5000 -13.2000
 1  41  83.8000   50.9000 -28.7000
 1  61 110.0000   73.8000 -30.6000
 1  71  24.8000   19.6000  -4.5000
 1  72    .0000    8.4000  -3.0000
 1  81  16.7000   10.1000  -1.9000
 1  91  16.1000   10.5000  -4.1000
 1 101  28.8000   20.0000  -6.0000
 1 111  49.8000   40.7000 -11.6000
 1 112    .0000   18.0000    .0000
 1 121  75.2000   53.0000 -23.7000
 1 122    .0000   16.8000 -11.5000
 1 132    .0000    6.6000  -3.6000
 10  32.3162  15.9858
 20     .2554  1.1679
 30  20.1657   7.7241
 40  67.6775  35.1601
 50     .1572  1.1061
 60  51.9516  32.3362
 70  58.8863  28.4989
 80    4.9800  4.8816
 90    2.9468  6.6675
100    5.5006  7.7365
110  37.5419  21.8932
120 168.7517 105.5670
130  24.6252   9.2751
 11.0000   .9999
 22.0000  1.010
 31.0000   .9997
 41.0000   .9999
 71.0000   .9999
 72.0000  1.0000
 81.0000  1.0001
 91.0000  1.0002
101.0000   .9999
```

111.0000	1.0000
112.0000	1.0000
121.0000	1.0000
122.0000	1.0000
132.0000	1.0000

Voltage Limits

28

1	10	1.0000	1.0250	.9500
2	11	1.0000	1.0250	.9500
3	20	1.0000	1.0250	.9500
4	22	1.0000	1.0250	.9500
5	30	1.0000	1.0250	.9500
6	31	1.0000	1.0250	.9500
7	40	1.0000	1.0250	.9500
8	41	1.0000	1.0250	.9500
9	50	1.0000	1.0250	.9500
10	60	1.0000	1.0250	.9500
11	61	1.0000	1.0250	.9500
12	70	1.0000	1.0250	.9500
13	71	1.0000	1.0250	.9500
14	72	1.0000	1.0250	.9500
15	80	1.0000	1.0250	.9500
16	81	1.0000	1.0250	.9500
17	90	1.0000	1.0250	.9500
18	91	1.0000	1.0250	.9500
19	100	1.0000	1.0250	.9500
20	101	1.0000	1.0250	.9500
21	110	1.0000	1.0250	.9500
22	111	1.0000	1.0250	.9500
23	112	1.0000	1.0250	.9500
24	120	1.0000	1.0250	.9500
25	121	1.0000	1.0250	.9500
26	122	1.0000	1.0250	.9500
27	130	1.0000	1.0250	.9500
28	132	1.0000	1.0250	.9500

Transmission Line Thermal Limits

69

10	11	.00	.00
10	20	.00	2000.00
10	20	.00	1000.00
10	30	.00	2000.00
10	30	.00	2000.00
20	22	.00	.00
20	30	.00	500.00
20	30	.00	500.00
20	40	.00	2000.00
20	40	.00	2000.00
30	31	.00	.00
30	60	.00	2000.00
30	60	.00	2000.00
30	60	.00	2000.00
30	60	.00	2000.00

40	41	.00	.00
40	50	.00	2000.00
40	60	.00	5000.00
40	70	.00	2000.00
40	70	.00	2000.00
40	70	.00	2000.00
50	60	.00	1000.00
50	70	.00	2000.00
60	61	.00	.00
60	90	.00	1000.00
60	90	.00	500.00
60	90	.00	2000.00
60	100	.00	2000.00
60	100	.00	2000.00
60	120	.00	2000.00
70	71	.00	.00
70	72	.00	.00
70	80	.00	5000.00
70	110	.00	2000.00
70	110	.00	2000.00
80	81	.00	.00
80	90	.00	2000.00
80	100	.00	2000.00
80	120	.00	2000.00
80	120	.00	2000.00
90	91	.00	.00
90	120	.00	2000.00
90	120	.00	2000.00
100	101	.00	.00
100	120	.00	2000.00
100	120	.00	2000.00
100	120	.00	2000.00
110	111	.00	.00
110	112	.00	.00
110	120	.00	5000.00
110	130	.00	2000.00
110	130	.00	2000.00
120	121	.00	.00
120	122	.00	.00
120	130	.00	2000.00
120	130	.00	2000.00
130	132	.00	.00
10	0	.00	.00
20	0	.00	.00
30	0	.00	.00
40	0	.00	.00
60	0	.00	.00
70	0	.00	.00
80	0	.00	.00
90	0	.00	.00
100	0	.00	.00
110	0	.00	.00
120	0	.00	.00
130	0	.00	.00

APPENDIX D: 306 BUS SYSTEM DATA

Transmission Line Parameters

306 521

1	1	2	.00120	.01280	.21885	.00000	.00000	.00000
1	1	2	.00120	.01280	.21885	.00000	.00000	.00000
1	1	3	.00050	.00530	.09200	.00000	.00000	.00000
1	1	3	.00050	.00530	.09200	.00000	.00000	.00000
1	1	4	.00060	.01070	.26100	.00000	.00000	.00000
1	1	4	.00060	.01070	.26100	.00000	.00000	.00000
2	1	5	.00000	.02050	.90000	.00000	.00000	.00000
2	1	5	.00000	.02050	.90000	.00000	.00000	.00000
1	1	36	.00160	.01640	.30540	.00000	.00000	.00000
1	1	36	.00160	.01640	.30540	.00000	.00000	.00000
1	1	70	.00160	.02760	.67370	.00000	.00000	.00000
1	1	70	.00160	.02760	.67370	.00000	.00000	.00000
2	2	6	.00000	.02050	1.00000	.00000	.00000	.00000
2	2	143	.00000	.03840	1.05000	.00000	.00000	.00000
2	2	144	.00000	.03840	1.05000	.00000	.00000	.00000
2	3	7	.00000	.02050	.90000	.00000	.00000	.00000
2	3	7	.00000	.02050	.90000	.00000	.00000	.00000
2	4	8	.00000	.02000	.98000	.00000	.00000	.00000
2	4	145	.00000	.03970	1.03000	.00000	.00000	.00000
2	4	146	.00000	.03970	1.03000	.00000	.00000	.00000
2	4	147	.00000	.03970	1.03000	.00000	.00000	.00000
2	4	148	.00000	.03970	1.03000	.00000	.00000	.00000
1	5	13	.01440	.06810	.02857	.00000	.00000	.00000
1	5	13	.01440	.06810	.02859	.00000	.00000	.00000
1	5	149	.00310	.02340	.01990	.00000	.00000	.00000
1	5	149	.00310	.02340	.01990	.00000	.00000	.00000
1	5	150	.00560	.01990	.00800	.00000	.00000	.00000
1	5	150	.00560	.01990	.00800	.00000	.00000	.00000
1	5	33	.00300	.01370	.00400	.00000	.00000	.00000
1	5	151	.01010	.04280	.01870	.00000	.00000	.00000
1	5	34	.01200	.05190	.02190	.00000	.00000	.00000
1	5	35	.01350	.06790	.02860	.00000	.00000	.00000
1	5	152	.00660	.03110	.01292	.00000	.00000	.00000
1	5	152	.00660	.03110	.01292	.00000	.00000	.00000
2	5	153	.00000	.10000	1.00000	.00000	.00000	.00000
2	5	153	.00000	.10000	1.00000	.00000	.00000	.00000
1	6	13	.00220	.01810	.01560	.00000	.00000	.00000
1	6	13	.00220	.01810	.01560	.00000	.00000	.00000
1	6	154	.00120	.00800	.01308	.00000	.00000	.00000
2	6	155	.00000	.04250	1.07000	.00000	.00000	.00000
2	6	156	.00000	.04250	1.07000	.00000	.00000	.00000
1	7	13	.00580	.02650	.01090	.00000	.00000	.00000
1	7	157	.00360	.01670	.00690	.00000	.00000	.00000
1	7	158	.00100	.00890	.31703	.00000	.00000	.00000
1	7	158	.00100	.00890	.31703	.00000	.00000	.00000
1	7	28	.00170	.00750	.14200	.00000	.00000	.00000
1	7	28	.00170	.00750	.14200	.00000	.00000	.00000
1	7	32	.00180	.00670	.00340	.00000	.00000	.00000
1	7	159	.00310	.01160	.00590	.00000	.00000	.00000
2	7	160	.00000	.10000	1.00000	.00000	.00000	.00000
2	7	160	.00000	.10000	1.00000	.00000	.00000	.00000
1	8	35	.00370	.02900	.02430	.00000	.00000	.00000
1	9	10	.00340	.01590	.00670	.00000	.00000	.00000

1	9	11	.00340	.01050	.00440	.00000	.00000	.00000
1	9	11	.00340	.01050	.00440	.00000	.00000	.00000
1	9	12	.00470	.02600	.01524	.00000	.00000	.00000
1	9	161	.01980	.07080	.02840	.00000	.00000	.00000
1	9	161	.01980	.07080	.02840	.00000	.00000	.00000
1	9	13	.01010	.03670	.01450	.00000	.00000	.00000
1	9	13	.01010	.03670	.01450	.00000	.00000	.00000
1	10	40	.00610	.02810	.01220	.00000	.00000	.00000
1	11	13	.00830	.04060	.01700	.00000	.00000	.00000
1	11	14	.00250	.01270	.00520	.00000	.00000	.00000
1	11	19	.00160	.00530	.26546	.00000	.00000	.00000
1	11	21	.00220	.00690	.36660	.00000	.00000	.00000
1	11	23	.00080	.00280	.17110	.00000	.00000	.00000
1	11	24	.00130	.00470	.17560	.00000	.00000	.00000
2	11	162	.00000	.07030	1.07000	.00000	.00000	.00000
2	11	163	.00000	.03100	1.05000	.00000	.00000	.00000
1	12	164	.00690	.03610	.01905	.00000	.00000	.00000
1	13	157	.00210	.00980	.00410	.00000	.00000	.00000
1	13	14	.00740	.03450	.01450	.00000	.00000	.00000
1	13	15	.00560	.01990	.00800	.00000	.00000	.00000
1	13	15	.00560	.01990	.00800	.00000	.00000	.00000
1	14	165	.00030	.00090	.06031	.00000	.00000	.00000
1	15	16	.00200	.01850	.01560	.00000	.00000	.00000
1	15	16	.00200	.01850	.01560	.00000	.00000	.00000
1	15	17	.00040	.00310	.23320	.00000	.00000	.00000
1	15	17	.00040	.00310	.23320	.00000	.00000	.00000
1	15	154	.00640	.01960	.00740	.00000	.00000	.00000
1	15	154	.00640	.01960	.00740	.00000	.00000	.00000
2	16	166	.00000	.08470	1.07000	.00000	.00000	.00000
2	16	167	.00000	.08470	1.07000	.00000	.00000	.00000
1	17	18	.00020	.00170	.08000	.00000	.00000	.00000
1	17	18	.00020	.00170	.08000	.00000	.00000	.00000
1	17	168	.00080	.00230	.10050	.00000	.00000	.00000
1	18	169	.00030	.00180	.12780	.00000	.00000	.00000
1	18	169	.00030	.00180	.12780	.00000	.00000	.00000
1	19	170	.00040	.00110	.05544	.00000	.00000	.00000
1	20	44	.00140	.00430	.22070	.00000	.00000	.00000
1	21	171	.00150	.00480	.24103	.00000	.00000	.00000
1	22	44	.00070	.00250	.11780	.00000	.00000	.00000
1	23	24	.00050	.00170	.10490	.00000	.00000	.00000
1	24	172	.00090	.00430	.00180	.00000	.00000	.00000
1	25	29	.00160	.00880	.16500	.00000	.00000	.00000
1	25	29	.00160	.00880	.16500	.00000	.00000	.00000
1	26	46	.00020	.00130	.10860	.00000	.00000	.00000
1	26	46	.00020	.00130	.10860	.00000	.00000	.00000
1	27	158	.00080	.00320	.19860	.00000	.00000	.00000
1	27	158	.00080	.00320	.19860	.00000	.00000	.00000
1	28	173	.00040	.00170	.10915	.00000	.00000	.00000
1	28	173	.00040	.00170	.10915	.00000	.00000	.00000
1	29	30	.00100	.00790	.00250	.00000	.00000	.00000
1	29	31	.00140	.01050	.00400	.00000	.00000	.00000
1	29	174	.00050	.00390	.24130	.00000	.00000	.00000
1	29	174	.00050	.00390	.24130	.00000	.00000	.00000
1	30	149	.00310	.02470	.01200	.00000	.00000	.00000
1	30	175	.00050	.00390	.36200	.00000	.00000	.00000
1	31	149	.00120	.00980	.00300	.00000	.00000	.00000
1	32	159	.00190	.00790	.00410	.00000	.00000	.00000
1	33	151	.00740	.03940	.00430	.00000	.00000	.00000
1	34	35	.00920	.03920	.01660	.00000	.00000	.00000

1	35	84	.01450	.06660	.02880	.00000	.00000	.00000
1	35	84	.01450	.06660	.02880	.00000	.00000	.00000
1	36	37	.00100	.01040	.17248	.00000	.00000	.00000
1	36	37	.00100	.01040	.17248	.00000	.00000	.00000
2	36	38	.00000	.02050	.90000	.00000	.00000	.00000
2	36	38	.00000	.02050	.90000	.00000	.00000	.00000
1	36	54	.00190	.03280	.80427	.00000	.00000	.00000
1	36	54	.00190	.03280	.80427	.00000	.00000	.00000
1	36	69	.00450	.04750	.80933	.00000	.00000	.00000
1	36	69	.00450	.04750	.80933	.00000	.00000	.00000
2	37	39	.00000	.02050	.88000	.00000	.00000	.00000
2	37	39	.00000	.02000	.88000	.00000	.00000	.00000
1	38	43	.00250	.01920	.01600	.00000	.00000	.00000
1	38	43	.00250	.01920	.01600	.00000	.00000	.00000
1	38	176	.00060	.00460	.00385	.00000	.00000	.00000
1	38	176	.00060	.00460	.00385	.00000	.00000	.00000
1	38	177	.00060	.00410	.16945	.00000	.00000	.00000
1	38	177	.00060	.00410	.16945	.00000	.00000	.00000
1	38	177	.00060	.00410	.16945	.00000	.00000	.00000
1	38	52	.00820	.06350	.05330	.00000	00000	.00000
1	38	52	.00820	.06350	.05330	.00000	.00000	.00000
2	38	178	.00000	.10000	1.00000	.00000	.00000	.00000
2	38	178	.00000	.10000	1.00000	.00000	.00000	.00000
1	39	40	.00180	.01410	.01193	.00000	.00000	.00000
1	39	40	.00180	.01410	.01193	.00000	.00000	.00000
1	39	42	.00290	.02250	.01910	.00000	.00000	.00000
1	39	42	.00290	.02250	.01910	.00000	.00000	.00000
1	39	179	.01230	.05760	.02360	.00000	.00000	.00000
1	39	179	.01230	.05760	.02360	.00000	.00000	.00000
2	39	180	.00000	.10000	1.00000	.00000	.00000	.00000
2	39	180	.00000	.10000	1.00000	.00000	.00000	.00000
1	40	164	.00350	.01640	.00700	.00000	.00000	.00000
1	40	43	.00860	.03880	.01696	.00000	.00000	.00000
1	40	43	.00860	.03880	.01696	.00000	.00000	.00000
1	41	42	.00080	.00260	.18500	.00000	.00000	.00000
1	41	42	.00080	.00260	.18500	.00000	.00000	.00000
1	41	181	.00060	.00410	.27000	.00000	.00000	.00000
1	42	181	.00080	.00560	.42230	.00000	.00000	.00000
1	43	182	.00490	.02010	.01130	.00000	.00000	.00000
1	43	45	.00420	.02460	.01070	.00000	.00000	.00000
1	43	47	.01140	.04910	.01980	.00000	.00000	.00000
1	43	47	.01140	.04910	.01980	.00000	.00000	.00000
1	43	47	.01020	.04750	.02010	.00000	.00000	.00000
1	43	51	.00590	.02120	.00858	.00000	.00000	.00000
1	43	53	.02570	.09090	.03676	.00000	.00000	.00000
1	43	183	.02900	.24380	.09860	.00000	.00000	.00000
1	44	182	.00040	.00240	.00130	.00000	.00000	.00000
1	44	45	.00220	.01230	.00530	.00000	.00000	.00000
1	45	184	.00030	.00200	.16000	.00000	.00000	.00000
1	45	184	.00030	.00200	.16000	.00000	.00000	.00000
1	46	185	.00350	.01790	.00776	.00000	.00000	.00000
1	46	177	.00030	.00240	.17500	.00000	.00000	.00000
1	47	48	.00250	.10330	.04395	.00000	.00000	.00000
1	47	49	.01780	.07170	.03120	.00000	.00000	.00000
1	47	50	.01820	.06370	.02370	.00000	.00000	.00000
2	47	186	.00000	.35360	1.05000	.00000	.00000	.00000
2	47	187	.00000	.45590	1.05000	.00000	.00000	.00000
2	47	188	.00000	.18670	1.05000	.00000	.00000	.00000
1	48	49	.00770	.03330	.01340	.00000	.00000	.00000

2	48	189	.00000	.35070	1.07000	.00000	.00000	.00000
2	48	190	.00000	.36680	1.07000	.00000	.00000	.00000
2	48	191	.00000	.36340	1.07000	.00000	.00000	.00000
2	48	192	.00000	.32860	1.07000	.00000	.00000	.00000
2	49	193	.00000	.32210	1.07000	.00000	.00000	.00000
2	49	194	.00000	.32310	1.07000	.00000	.00000	.00000
2	50	195	.00000	.42880	1.05000	.00000	.00000	.00000
2	50	196	.00000	.43160	1.05000	.00000	.00000	.00000
2	51	197	.00000	.57430	1.03000	.00000	.00000	.00000
2	51	198	.00000	.57520	1.03000	.00000	.00000	.00000
2	51	199	.00000	.57520	1.03000	.00000	.00000	.00000
2	51	200	.00000	.57660	1.03000	.00000	.00000	.00000
2	52	201	.00000	.04970	1.05000	.00000	.00000	.00000
2	52	202	.00000	.04970	1.05000	.00000	.00000	.00000
1	53	203	.01230	.05790	.02399	.00000	.00000	.00000
1	53	203	.01230	.05790	.02399	.00000	.00000	.00000
1	53	183	.04330	.15290	.06220	.00000	.00000	.00000
1	54	55	.00140	.02520	.61211	.00000	.00000	.00000
1	54	55	.00140	.02520	.61211	.00000	.00000	.00000
2	54	56	.00000	.02000	.96000	.00000	.00000	.00000
1	54	98	.00300	.05340	1.28264	.00000	.00000	.00000
1	54	98	.00300	.05340	1.28264	.00000	.00000	.00000
2	55	57	.00000	.02000	.96000	.00000	.00000	.00000
1	56	183	.00470	.02170	.00920	.00000	.00000	.00000
1	56	183	.00470	.02170	.00920	.00000	.00000	.00000
1	56	64	.01610	.07640	.03295	.00000	.00000	.00000
1	56	65	.04440	.21390	.08962	.00000	.00000	.00000
1	56	67	.00790	.06190	.04830	.00000	.00000	.00000
1	56	67	.00790	.06190	.04830	.00000	.00000	.00000
2	56	204	.00000	.10000	1.00000	.00000	.00000	.00000
1	57	58	.01850	.12320	.09525	.00000	.00000	.00000
1	57	58	.01850	.12320	.09525	.00000	.00000	.00000
1	57	61	.00590	.03990	.03130	.00000	.00000	.00000
1	57	62	.00100	.00450	.00410	.00000	.00000	.00000
1	57	62	.00100	.00450	.00410	.00000	.00000	.00000
1	57	63	.00930	.06310	.04875	.00000	.00000	.00000
2	57	205	.00000	.10000	1.00000	.00000	.00000	.00000
1	58	59	.01080	.05270	.02000	.00000	.00000	.00000
1	58	60	.02740	.09730	.03910	.00000	.00000	.00000
1	58	60	.02740	.09730	.03910	.00000	.00000	.00000
1	58	183	.01650	.05760	.02340	.00000	.00000	.00000
1	58	183	.01650	.05760	.02340	.00000	.00000	.00000
1	58	104	.03920	.18590	.07560	.00000	.00000	.00000
2	58	206	.00000	.10580	1.05000	.00000	.00000	.00000
2	58	207	.00000	.10580	1.05000	.00000	.00000	.00000
2	58	208	.00000	.09360	1.05000	.00000	.00000	.00000
2	58	209	.00000	.09360	1.05000	.00000	.00000	.00000
2	58	210	.00000	.11540	1.05000	.00000	.00000	.00000
2	58	211	.00000	.11540	1.05000	.00000	.00000	.00000
2	58	212	.00000	.11540	1.05000	.00000	.00000	.00000
1	59	104	.02860	.13450	.05140	.00000	.00000	.00000
1	60	62	.02470	.08770	.03610	.00000	.00000	.00000
1	60	62	.02470	.08770	.03610	.00000	.00000	.00000
1	61	62	.01630	.06200	.02270	.00000	.00000	.00000
1	61	62	.01630	.06200	.02270	.00000	.00000	.00000
1	61	63	.00410	.02850	.01614	.00000	.00000	.00000
2	61	213	.00000	.07410	1.06000	.00000	.00000	.00000
2	61	214	.00000	.04650	1.09000	.00000	.00000	.00000
1	62	215	.03300	.10700	.00780	.00000	.00000	.00000

1	62	215	.03300	.10700	.00780	.00000	.00000	.00000
1	63	216	.02670	.12910	.05216	.00000	.00000	.00000
1	63	216	.02670	.12910	.05216	.00000	.00000	.00000
1	64	66	.03010	.14310	.06010	.00000	.00000	.00000
1	65	66	.00610	.02900	.01210	.00000	.00000	.00000
2	66	217	.00000	.09420	1.05000	.00000	.00000	.00000
2	66	218	.00000	.09420	1.05000	.00000	.00000	.00000
1	67	68	.00130	.01050	.00821	.00000	.00000	.00000
1	67	68	.00130	.01050	.00821	.00000	.00000	.00000
2	68	219	.00000	.07510	1.07000	.00000	.00000	.00000
2	68	220	.00000	.07510	1.07000	.00000	.00000	.00000
2	68	221	.00000	.07510	1.07000	.00000	.00000	.00000
2	68	222	.00000	.07510	1.07000	.00000	.00000	.00000
1	69	70	.00120	.02030	.49480	.00000	.00000	.00000
1	69	70	.00120	.02030	.49480	.00000	.00000	.00000
2	69	72	.00000	.02050	.92000	.00000	.00000	.00000
2	69	72	.00000	.02050	.92000	.00000	.00000	.00000
1	69	85	.00280	.03080	.50580	.00000	.00000	.00000
1	69	85	.00280	.03080	.50580	.00000	.00000	.00000
1	69	97	.00340	.03540	.61079	.00000	.00000	.00000
1	69	97	.00340	.03540	.61079	.00000	.00000	.00000
1	70	71	.00040	.00770	.18740	.00000	.00000	.00000
1	70	71	.00040	.00770	.18740	.00000	.00000	.00000
1	70	88	.00250	.04350	1.06280	.00000	.00000	.00000
1	70	88	.00250	.04350	1.06280	.00000	.00000	.00000
2	71	223	.00000	.02790	1.08000	.00000	.00000	.00000
2	71	224	.00000	.02790	1.08000	.00000	.00000	.00000
1	72	73	.00220	.01600	.00720	.00000	.00000	.00000
1	72	73	.00220	.01600	.00720	.00000	.00000	.00000
1	72	73	.00450	.01810	.00740	.00000	.00000	.00000
1	72	225	.01240	.04620	.01873	.00000	.00000	.00000
1	72	78	.00740	.05860	.04920	.00000	.00000	.00000
1	72	78	.00740	.05860	.04920	.00000	.00000	.00000
1	72	84	.02990	.13870	.05840	.00000	.00000	.00000
1	72	226	.02100	.09900	.04164	.00000	.00000	.00000
1	72	104	.03450	.11500	.04620	.00000	.00000	.00000
1	72	104	.03450	.11500	.04620	.00000	.00000	.00000
2	72	227	.00000	.10000	1.00000	.00000	.00000	.00000
2	72	227	.00000	.10000	1.00000	.00000	.00000	.00000
1	73	225	.00790	.02800	.01090	.00000	.00000	.00000
1	73	74	.00290	.01370	.00610	.00000	.00000	.00000
1	73	228	.00790	.03110	.01291	.00000	.00000	.00000
1	73	81	.03580	.13630	.05230	.00000	.00000	.00000
1	73	81	.03580	.13630	.05230	.00000	.00000	.00000
1	74	75	.00280	.01320	.00550	.00000	.00000	.00000
1	75	76	.00820	.03850	.01200	.00000	.00000	.00000
1	76	77	.01170	.04200	.01690	.00000	.00000	.00000
2	76	229	.00000	.20000	1.08000	.00000	.00000	.00000
2	76	230	.00000	.20000	1.08000	.00000	.00000	.00000
1	77	228	.01450	.05220	.02025	.00000	.00000	.00000
1	78	79	.00830	.06560	.07200	.00000	.00000	.00000
1	78	80	.00900	.11610	.05870	.00000	.00000	.00000
1	78	231	.00490	.03820	.03202	.00000	.00000	.00000
1	78	81	.00570	.04500	.03740	.00000	.00000	.00000
1	79	232	.00560	.04510	.03772	.00000	.00000	.00000
1	79	231	.01060	.07620	.06811	.00000	.00000	.00000
2	79	233	.00000	.04400	1.05000	.00000	.00000	.00000
2	79	234	.00000	.04400	1.05000	.00000	.00000	.00000
1	80	81	.01130	.04090	.01670	.00000	.00000	.00000

1	80	235	.00630	.02350	.00960	.00000	.00000	.00000
2	80	236	.00000	.14060	1.05000	.00000	.00000	.00000
2	80	237	.00000	.09360	1.05000	.00000	.00000	.00000
2	80	238	.00000	.09360	1.05000	.00000	.00000	.00000
2	80	239	.00000	.08920	1.05000	.00000	.00000	.00000
2	80	240	.00000	.08920	1.05000	.00000	.00000	.00000
2	80	241	.00000	.08920	1.05000	.00000	.00000	.00000
1	81	235	.01650	.05810	.02370	.00000	.00000	.00000
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1	81	83	.00890	.03420	.01379	.00000	.00000	.00000
1	82	91	.03070	.11310	.04620	.00000	.00000	.00000
1	83	91	.04590	.16540	.06723	.00000	.00000	.00000
1	84	226	.01160	.05520	.02318	.00000	.00000	.00000
1	85	86	.00270	.02980	.48910	.00000	.00000	.00000
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1	85	87	.00090	.01530	.37512	.00000	.00000	.00000
1	85	87	.00090	.01530	.37512	.00000	.00000	.00000
1	85	116	.00160	.02710	.67380	.00000	.00000	.00000
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2	86	89	.00000	.02100	.98000	.00000	.00000	.00000
2	86	242	.00000	.04800	1.05000	.00000	.00000	.00000
1	87	88	.00080	.01430	.34640	.00000	.00000	.00000
1	87	88	.00080	.01430	.34640	.00000	.00000	.00000
2	87	90	.00000	.02000	1.01000	.00000	.00000	.00000
2	88	243	.00000	.01390	1.05000	.00000	.00000	.00000
2	88	244	.00000	.01390	1.05000	.00000	.00000	.00000
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1	89	94	.00800	.05770	.02540	.00000	.00000	.00000
1	89	95	.00070	.00620	.00530	.00000	.00000	.00000
1	89	95	.00070	.00620	.00530	.00000	.00000	.00000
2	89	245	.00000	.04600	1.02000	.00000	.00000	.00000
2	89	246	.00000	.10000	1.00000	.00000	.00000	.00000
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1	90	91	.00200	.01840	.01240	.00000	.00000	.00000
1	90	92	.00120	.00960	.01173	.00000	.00000	.00000
1	90	92	.00120	.00960	.01173	.00000	.00000	.00000
2	90	247	.00000	.10000	1.00000	.00000	.00000	.00000
1	91	94	.03930	.13980	.05640	.00000	.00000	.00000
1	91	248	.00260	.00930	.03700	.00000	.00000	.00000
1	92	93	.01330	.06190	.02580	.00000	.00000	.00000
1	92	93	.01330	.06190	.02580	.00000	.00000	.00000
1	92	96	.03700	.20160	.08630	.00000	.00000	.00000
1	92	249	.03700	.20020	.11400	.00000	.00000	.00000
1	93	250	.01770	.08320	.03460	.00000	.00000	.00000
1	93	250	.01770	.08320	.03460	.00000	.00000	.00000
1	93	251	.01800	.08490	.03530	.00000	.00000	.00000
1	93	251	.01800	.08490	.03530	.00000	.00000	.00000
1	94	248	.03690	.13100	.05300	.00000	.00000	.00000
1	94	128	.02380	.12550	.05260	.00000	.00000	.00000
1	94	252	.01240	.06550	.02750	.00000	.00000	.00000
1	95	96	.00210	.01600	.01337	.00000	.00000	.00000
1	95	96	.00210	.01600	.01337	.00000	.00000	.00000
2	95	253	.00000	.04120	1.04000	.00000	.00000	.00000
2	95	254	.00000	.04120	1.04000	.00000	.00000	.00000
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2	97	100	.00000	.01990	.94000	.00000	.00000	.00000

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1	97	114	.00390	.04000	.69020	.00000	.00000	.00000
1	97	114	.00390	.04000	.69020	.00000	.00000	.00000
1	98	99	.00040	.00670	.16440	.00000	.00000	.00000
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1	98	121	.00120	.02020	.49392	.00000	.00000	.00000
1	98	121	.00120	.02020	.49392	.00000	.00000	.00000
2	99	255	.00000	.01750	1.05000	.00000	.00000	.00000
1	100	102	.01060	.05010	.02080	.00000	.00000	.00000
1	100	102	.01060	.05010	.02080	.00000	.00000	.00000
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1	100	104	.03930	.17760	.07290	.00000	.00000	.00000
1	100	256	.01150	.05230	.02230	.00000	.00000	.00000
1	100	257	.01150	.05200	.02220	.00000	.00000	.00000
1	100	258	.00290	.01440	.01360	.00000	.00000	.00000
1	100	258	.00290	.01440	.01360	.00000	.00000	.00000
1	100	111	.00710	.05610	.04692	.00000	.00000	.00000
1	100	111	.00710	.05610	.04692	.00000	.00000	.00000
2	100	259	.00000	.10000	1.00000	.00000	.00000	.00000
2	100	259	.00000	.10000	1.00000	.00000	.00000	.00000
2	100	259	.00000	.10000	1.00000	.00000	.00000	.00000
1	101	113	.00120	.00980	.00820	.00000	.00000	.00000
1	101	113	.00120	.00980	.00820	.00000	.00000	.00000
1	101	260	.00370	.02040	.00890	.00000	.00000	.00000
1	101	260	.00370	.02040	.00890	.00000	.00000	.00000
2	101	261	.00000	.10000	1.00000	.00000	.00000	.00000
2	101	261	.00000	.10000	1.00000	.00000	.00000	.00000
1	102	103	.00460	.01160	.01130	.00000	.00000	.00000
1	102	262	.01720	.07070	.03170	.00000	.00000	.00000
1	103	262	.01260	.05910	.02467	.00000	.00000	.00000
1	104	105	.03360	.12600	.04900	.00000	.00000	.00000
1	105	106	.00160	.00610	.00240	.00000	.00000	.00000
2	106	263	.00000	.23030	1.05000	.00000	.00000	.00000
2	106	264	.00000	.23030	1.05000	.00000	.00000	.00000
1	107	256	.00340	.01410	.00570	.00000	.00000	.00000
1	107	257	.00340	.01430	.00580	.00000	.00000	.00000
1	107	265	.00570	.02010	.00810	.00000	.00000	.00000
1	107	111	.00840	.03960	.01656	.00000	.00000	.00000
1	107	111	.00840	.03960	.01656	.00000	.00000	.00000
1	107	127	.03770	.14580	.05130	.00000	.00000	.00000
1	107	127	.03260	.13500	.00240	.00000	.00000	.00000
1	108	258	.00630	.04240	.01330	.00000	.00000	.00000
1	108	258	.00630	.04240	.01330	.00000	.00000	.00000
1	109	258	.00080	.00560	.22715	.00000	.00000	.00000
1	109	258	.00080	.00560	.22715	.00000	.00000	.00000
1	110	111	.00250	.01200	.00520	.00000	.00000	.00000
1	110	113	.03860	.15540	.07890	.00000	.00000	.00000
1	111	112	.01350	.06440	.02696	.00000	.00000	.00000
1	112	266	.04250	.17740	.07650	.00000	.00000	.00000
1	113	266	.01260	.04480	.01865	.00000	.00000	.00000
1	113	260	.00150	.00730	.00290	.00000	.00000	.00000
1	113	138	.01990	.10810	.04540	.00000	.00000	.00000
1	113	138	.01990	.10810	.04540	.00000	.00000	.00000
1	114	115	.00120	.01230	.21300	.00000	.00000	.00000
1	114	115	.00120	.01230	.21300	.00000	.00000	.00000
1	114	119	.00070	.00700	.12130	.00000	.00000	.00000
1	114	119	.00070	.00700	.12130	.00000	.00000	.00000

2	114	122	.00000	.02100	.98000	.00000	.00000	.00000
2	114	122	.00000	.02100	.98000	.00000	.00000	.00000
1	115	116	.00090	.01540	.37600	.00000	.00000	.00000
1	115	116	.00090	.01540	.37600	.00000	.00000	.00000
1	115	117	.00030	.00520	.12760	.00000	.00000	.00000
1	115	117	.00030	.00520	.12760	.00000	.00000	.00000
1	115	120	.00080	.01320	.32080	.00000	.00000	.00000
1	115	120	.00080	.01320	.32080	.00000	.00000	.00000
2	115	123	.00000	.02050	.95000	.00000	.00000	.00000
2	115	123	.00000	.02050	.95000	.00000	.00000	.00000
2	115	123	.00000	.02050	.95000	.00000	.00000	.00000
1	116	118	.00090	.01570	.38390	.00000	.00000	.00000
1	116	118	.00090	.01570	.38390	.00000	.00000	.00000
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2	116	124	.00000	.02000	.97000	.00000	.00000	.00000
1	117	121	.00030	.00540	.13270	.00000	.00000	.00000
1	117	121	.00030	.00540	.13270	.00000	.00000	.00000
2	117	125	.00000	.02050	1.00000	.00000	.00000	.00000
2	118	267	.00000	.02060	1.05000	.00000	.00000	.00000
2	118	268	.00000	.02060	1.05000	.00000	.00000	.00000
2	119	269	.00000	.02500	1.05000	.00000	.00000	.00000
2	119	270	.00000	.02500	1.05000	.00000	.00000	.00000
2	120	271	.00000	.03050	1.05000	.00000	.00000	.00000
2	120	272	.00000	.03050	1.05000	.00000	.00000	.00000
2	120	273	.00000	.03050	1.05000	.00000	.00000	.00000
2	121	274	.00000	.01390	1.05000	.00000	.00000	.00000
2	121	275	.00000	.01390	1.05000	.00000	.00000	.00000
1	122	123	.02710	.12810	.05350	.00000	.00000	.00000
1	122	136	.02280	.08040	.03260	.00000	.00000	.00000
1	122	276	.01330	.04720	.01917	.00000	.00000	.00000
1	122	277	.01890	.08930	.03730	.00000	.00000	.00000
1	122	138	.00240	.01840	.01560	.00000	.00000	.00000
1	122	278	.00130	.00690	.00290	.00000	.00000	.00000
1	122	278	.00130	.00690	.00290	.00000	.00000	.00000
1	122	139	.00290	.02130	.00920	.00000	.00000	.00000
1	122	139	.00290	.02130	.00920	.00000	.00000	.00000
1	122	140	.00180	.01380	.01110	.00000	.00000	.00000
1	122	140	.00180	.01390	.01170	.00000	.00000	.00000
1	122	279	.00130	.01090	.00650	.00000	.00000	.00000
2	122	280	.00000	.10000	1.00000	.00000	.00000	.00000
2	122	280	.00000	.10000	1.00000	.00000	.00000	.00000
1	123	127	.01980	.06990	.02838	.00000	.00000	.00000
1	123	281	.01510	.05370	.01630	.00000	.00000	.00000
1	123	130	.00670	.02380	.00960	.00000	.00000	.00000
1	123	131	.00650	.02280	.00920	.00000	.00000	.00000
1	123	133	.01030	.03620	.00270	.00000	.00000	.00000
1	123	133	.01030	.03620	.00270	.00000	.00000	.00000
1	123	134	.00110	.00830	.00710	.00000	.00000	.00000
1	123	134	.00110	.00830	.00710	.00000	.00000	.00000
1	123	136	.00580	.02030	.00823	.00000	.00000	.00000
1	123	136	.00580	.02030	.00823	.00000	.00000	.00000
1	123	277	.00820	.03890	.01620	.00000	.00000	.00000
1	123	142	.00790	.06140	.05292	.00000	.00000	.00000
1	123	142	.00790	.06140	.05292	.00000	.00000	.00000
1	123	142	.00790	.06140	.05292	.00000	.00000	.00000
1	123	142	.00790	.06140	.05292	.00000	.00000	.00000
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2	123	282	.00000	.10000	1.00000	.00000	.00000	.00000
2	123	282	.00000	.10000	1.00000	.00000	.00000	.00000

1	124	283	.00450	.02680	.01120	.00000	.00000	.00000
1	124	283	.00450	.02680	.01120	.00000	.00000	.00000
1	124	284	.00370	.02470	.01950	.00000	.00000	.00000
1	124	284	.00370	.02470	.01950	.00000	.00000	.00000
1	124	128	.01890	.08810	.03726	.00000	.00000	.00000
1	124	128	.01890	.08810	.03726	.00000	.00000	.00000
2	124	285	.00000	.10000	1.00000	.00000	.00000	.00000
2	124	285	.00000	.10000	1.00000	.00000	.00000	.00000
1	125	286	.00160	.01280	.01077	.00000	.00000	.00000
1	125	286	.00160	.01280	.01077	.00000	.00000	.00000
2	125	287	.00000	.10000	1.00000	.00000	.00000	.00000
1	126	128	.01510	.07660	.03255	.00000	.00000	.00000
1	126	128	.01510	.07660	.03255	.00000	.00000	.00000
1	126	141	.02620	.12160	.05110	.00000	.00000	.00000
1	126	288	.00810	.03790	.01738	.00000	.00000	.00000
1	127	283	.00850	.03610	.01490	.00000	.00000	.00000
1	127	283	.00850	.03610	.01490	.00000	.00000	.00000
1	127	281	.01510	.05370	.01630	.00000	.00000	.00000
1	128	129	.00300	.01380	.00585	.00000	.00000	.00000
1	128	252	.02280	.11400	.04737	.00000	.00000	.00000
1	129	289	.02410	.11220	.04706	.00000	.00000	.00000
1	130	132	.00690	.02720	.01170	.00000	.00000	.00000
1	131	133	.00380	.01330	.00540	.00000	.00000	.00000
1	132	133	.00230	.00840	.00330	.00000	.00000	.00000
1	133	290	.00110	.00560	.04535	.00000	.00000	.00000
1	133	291	.00250	.00690	.02360	.00000	.00000	.00000
2	133	292	.00000	.10530	1.05000	.00000	.00000	.00000
2	133	293	.00000	.10530	1.05000	.00000	.00000	.00000
2	133	294	.00000	.09840	1.05000	.00000	.00000	.00000
2	133	295	.00000	.09840	1.05000	.00000	.00000	.00000
1	134	135	.00090	.00700	.15823	.00000	.00000	.00000
1	134	135	.00090	.00700	.15823	.00000	.00000	.00000
1	135	137	.00110	.00530	.05274	.00000	.00000	.00000
1	135	137	.00110	.00530	.05487	.00000	.00000	.00000
1	135	296	.00040	.00270	.19200	.00000	.00000	.00000
1	135	296	.00040	.00270	.19200	.00000	.00000	.00000
1	136	137	.00480	.01620	.00656	.00000	.00000	.00000
1	136	137	.00480	.01620	.00656	.00000	.00000	.00000
1	136	276	.02450	.08660	.03521	.00000	.00000	.00000
1	137	286	.00080	.00600	.16690	.00000	.00000	.00000
1	137	286	.00080	.00600	.15000	.00000	.00000	.00000
1	138	297	.00830	.04030	.01630	.00000	.00000	.00000
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1	138	140	.00370	.02880	.02580	.00000	.00000	.00000
2	139	298	.00000	.04650	1.06000	.00000	.00000	.00000
2	139	299	.00000	.04200	1.07000	.00000	.00000	.00000
1	140	279	.00220	.01740	.01459	.00000	.00000	.00000
2	140	300	.00000	.03960	1.06000	.00000	.00000	.00000
2	140	301	.00000	.03960	1.06000	.00000	.00000	.00000
2	140	302	.00000	.03960	1.06000	.00000	.00000	.00000
2	140	303	.00000	.09600	1.06000	.00000	.00000	.00000
2	140	304	.00000	.09600	1.06000	.00000	.00000	.00000
1	141	288	.01050	.04890	.02683	.00000	.00000	.00000
2	142	305	.00000	.02860	1.05000	.00000	.00000	.00000
2	142	306	.00000	.02860	1.05000	.00000	.00000	.00000

Generator and Load Pattern

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  38  171   37  163  1.0000    .0000    .0000  1.0000
 1  155   2.0000   1.6000
 1  156   2.0000   1.6000
 1  143   2.7000   2.2700
 1  163   2.5000   1.0000
 1  145   2.5000   1.7500
 1  146   2.5000   1.7500
 1  197    .2000    .3300
 1  198    .2000    .3300
 1  186    .2000    .0900
 1  187    .2000    .0900
 1  189    .0500    .1300
 1  190    .0500    .1300
 1  191    .0500    .1300
 1  192    .0500    .1300
 1  193    .2500    .1300
 1  201   1.5000    .4000
 1  195    .2000    .1000
 1  214   1.8000   1.2400
 1  219    .5000    .7000
 1  220    .5000    .7000
 1  217    .8000    .4500
 1  223   5.0000   2.8000
 1  224   5.0000   2.8000
 1  229    .4000    .2100
 1  233   1.8000   1.2400
 1  253   2.0000   1.7400
 1  243   9.5000   4.5000
 1  244   9.5000   4.5000
 1  255   6.7900   4.2100
 1  267   5.0000   3.0000
 1  268   5.0000   3.0000
 1  269   5.8700   3.6400
 1  270   6.5000   4.0300
 1  274   9.5000   5.5000
 1  275   9.5000   5.5000
 1  272   2.8400   2.4800
 1  305   2.5000   2.1000
 1  306   2.5000   2.1000
  5    .0200    .0000
  6   1.2800   1.1600
  7    .7800    .2600
  9   1.0000   -.1400
 10    .2800    .1300
 11    .3700    .1000
 12    .3100    .0900
161    .3100    .0900
 13   2.9100   1.6900
157   1.7200    .8200
 14    .8500    .2700
 15   1.9300    .7300
 17    .5300    .1200
154    .9200    .1900
 18    .8900    .2400
 19    .9100    .2800
 20    .7100    .2300
 21    .3100    .1000
 22    .5000    .1900
 23    .5600    .1600
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24	.7000	.2900
172	.1900	.1000
25	.5300	.1900
26	.4600	.2300
27	.4100	.1600
158	1.1000	.4400
28	1.2000	.6000
29	1.1800	.1700
30	.6600	.2900
31	.1500	.0600
149	.7400	.3000
32	1.0800	.3200
159	.5100	.2800
150	1.2800	.6200
33	1.1300	.5900
151	1.3600	.5400
34	.8600	.4400
35	.6500	.2700
152	1.2200	.4900
38	.5200	.1700
40	.9100	.5900
164	.5600	.2000
41	.7000	.4100
42	.7000	.3800
181	.4600	.1600
179	.5800	.2300
43	.6500	.2400
44	.7400	.3400
182	.7800	.1700
45	.5100	.2100
184	.8000	.3700
46	.4100	.1200
185	.9700	.3800
177	.4300	.1500
47	.0300	.0100
48	.0300	.0100
49	.0600	.0100
53	1.3600	.3200
56	.9300	.4600
57	1.8700	.7300
58	.3900	.0600
59	.4600	.1200
60	1.0400	-.0100
62	.8400	.3400
63	.2300	.1200
216	.1000	-.0800
183	.2300	-.0400
64	.5000	.1700
65	.2300	.1000
67	.2900	.1200
72	.1700	.0600
73	.5200	.1900
225	.7400	.3700
74	.4900	.2300
75	.2400	.1200
77	1.3200	.4900
228	.4800	.2300
78	.1600	.0500
80	.1900	-.0500

232	.1700	.0600
231	.1300	.0100
81	1.3500	.2600
235	.8400	.2800
82	.3800	.0900
83	.2800	.0600
84	1.7100	.6100
226	.2300	.1200
89	.2200	.0900
91	.5600	.1300
92	.6200	.1000
93	.4600	-.1800
250	.3100	-.0300
251	.2700	-.1500
94	.5900	.2600
248	.3200	.0400
95	.1600	.0300
96	1.7100	.4300
249	.2200	.0900
102	.5300	.2300
103	1.6400	.6400
262	.2100	.0900
104	.4600	.1000
105	.4800	.1300
107	.9200	.1500
256	1.0300	.4800
257	.7700	.3000
265	.3700	.1000
108	.8200	.0300
109	.5800	.2300
258	1.4400	.5200
110	.6700	.2300
111	.3600	.0900
112	.2300	.0600
113	1.3900	.3500
266	.3600	.0200
260	.2300	.2300
122	.2700	.0900
123	.3100	.0600
124	.5200	.1700
127	.4100	-.2000
283	1.5700	.2800
284	2.2700	.4100
128	.5200	-.0400
129	.3000	.0800
289	.1200	-.0900
281	.1500	.0300
130	1.2100	.5000
131	1.3300	.6400
132	.5100	.2300
133	.5900	.2200
290	.4600	.1200
291	.7200	.1900
134	.8100	.3500
135	.4500	.1200
136	.9500	.2700
137	1.9000	.4900
296	.3000	.0500
276	.2100	.1000

```
  286   .4200   .1900
  277   .6700   .2200
  138  1.8000  1.0500
  297   .3700   .1200
  278  1.5300   .6500
  140   .7300   .4100
  279  1.0400   .4100
  141   .3600   .1500
  288   .3100   .1200
  155   .1000   .0500
  156   .1000   .0500
  143   .1000   .0500
  163   .1100   .0500
  145   .1100   .0500
  146   .1100   .0500
  214   .1400   .0700
  219   .0100   .0000
  220   .0100   .0000
  217   .0100   .0000
  223   .3000   .1500
  224   .3000   .1500
  233   .2000   .1000
  253   .2500   .1200
  243   .6500   .3000
  244   .6500   .3000
  255   .4400   .2200
  267   .2700   .1300
  268   .2700   .1300
  269   .3700   .1800
  270   .4200   .2100
  274   .6500   .3200
  275   .6500   .3200
  272   .2000   .1200
155.0000   1.0000
156.0000   1.0000
143.0000   1.0000
145.0000   1.0000
146.0000   1.0000
197.0000   1.0000
198.0000   1.0000
186.0000   1.0000
187.0000   1.0000
189.0000   1.0000
190.0000   1.0000
191.0000   1.0000
192.0000   1.0000
193.0000   1.0000
201.0000   1.0000
195.0000   1.0000
214.0000   1.0000
219.0000   1.0000
220.0000   1.0000
217.0000   1.0000
223.0000   1.0000
224.0000   1.0000
229.0000   1.0000
233.0000   1.0000
253.0000   1.0000
243.0000   1.0000
```

244.0000	1.0000
255.0000	1.0000
267.0000	1.0000
268.0000	1.0000
269.0000	1.0000
270.0000	1.0000
274.0000	1.0000
275.0000	1.0000
272.0000	1.0000
305.0000	1.0000
306.0000	1.0000

APPENDIX E: SINGULAR VALUE DECOMPOSITION [162, 163]

The use of the singularity of power flow Jacobian matrix as an indictor of steady-state stability was first proposed by Venikov et al [162], where the sign of the determinant of J was used to determine whether the studied operating point was stable or not. The minimum singular value of power flow Jacobian matrix J, has been proposed as a static voltage stability index, in which the minimum singular value is used to indicate the distance between the studies operating point and the static voltage stability limit.

The singular value decomposition is an important and practically useful orthogonal decomposition method used for matrix computations. If matrix A is an n by n quadratic real matrix, then the singular value decomposition is given by:

$$A = U\sum V^T = \sum \sigma_i u_i v_i^T \tag{E-1}$$

where U and V are n by n orthonormal matrices, the singular vectors u_i and v_i are columns of matrices U and V respectively.

If the matrix A has rank r ($r <= n$) its singular value are the square roots of the r positive eigenvalue of A^TA, which also are r positive eigenvalue of A^TA. The smallest singular value of the matrix A is a measure of the distance, in which l_2-norm, between A and the set of all rank-deficient matrices.

The minimum singular value, is a measure of how close to singularity the power flow Jacobian matrix is. If the minimum singular value is equal to zero, the studied matrix is singular and no power flow solution can be obtained. The singularity of the Jacobian matrix corresponds to that the inverse of the matrix does not exist. This can be interpreted as an infinite sensitivity of power flow solution to perturbations in the parameters values. At the point where several branches of equilibria may come together and the studies system will experience a qualitative change in the structure of the solutions due to a change in the parameters values. In conclusion, the smallest singular value is an indicator of proximity to the steady-state stability limit. In the thesis, it is used to compare the results obtained by the proposed algorithm.

APPENDIX C: 306 BUS SYSTEM DATA

Transmission Line Parameters

306 521

1	1	2	.00120	.01280	.21885	.00000	.00000	.00000
1	1	2	.00120	.01280	.21885	.00000	.00000	.00000
1	1	3	.00050	.00530	.09200	.00000	.00000	.00000
1	1	3	.00050	.00530	.09200	.00000	.00000	.00000
1	1	4	.00060	.01070	.26100	.00000	.00000	.00000
1	1	4	.00060	.01070	.26100	.00000	.00000	.00000
2	1	5	.00000	.02050	.90000	.00000	.00000	.00000
2	1	5	.00000	.02050	.90000	.00000	.00000	.00000
1	1	36	.00160	.01640	.30540	.00000	.00000	.00000
1	1	36	.00160	.01640	.30540	.00000	.00000	.00000
1	1	70	.00160	.02760	.67370	.00000	.00000	.00000
1	1	70	.00160	.02760	.67370	.00000	.00000	.00000
2	2	6	.00000	.02050	1.00000	.00000	.00000	.00000
2	2	143	.00000	.03840	1.05000	.00000	.00000	.00000
2	2	144	.00000	.03840	1.05000	.00000	.00000	.00000
2	3	7	.00000	.02050	.90000	.00000	.00000	.00000
2	3	7	.00000	.02050	.90000	.00000	.00000	.00000
2	4	8	.00000	.02000	.98000	.00000	.00000	.00000
2	4	145	.00000	.03970	1.03000	.00000	.00000	.00000
2	4	146	.00000	.03970	1.03000	.00000	.00000	.00000
2	4	147	.00000	.03970	1.03000	.00000	.00000	.00000
2	4	148	.00000	.03970	1.03000	.00000	.00000	.00000
1	5	13	.01440	.06810	.02857	.00000	.00000	.00000
1	5	13	.01440	.06810	.02859	.00000	.00000	.00000
1	5	149	.00310	.02340	.01990	.00000	.00000	.00000
1	5	149	.00310	.02340	.01990	.00000	.00000	.00000
1	5	150	.00560	.01990	.00800	.00000	.00000	.00000
1	5	150	.00560	.01990	.00800	.00000	.00000	.00000
1	5	33	.00300	.01370	.00400	.00000	.00000	.00000
1	5	151	.01010	.04280	.01870	.00000	.00000	.00000
1	5	34	.01200	.05190	.02190	.00000	.00000	.00000
1	5	35	.01350	.06790	.02860	.00000	.00000	.00000
1	5	152	.00660	.03110	.01292	.00000	.00000	.00000
1	5	152	.00660	.03110	.01292	.00000	.00000	.00000
2	5	153	.00000	.10000	1.00000	.00000	.00000	.00000
2	5	153	.00000	.10000	1.00000	.00000	.00000	.00000
1	6	13	.00220	.01810	.01560	.00000	.00000	.00000
1	6	13	.00220	.01810	.01560	.00000	.00000	.00000
1	6	154	.00120	.00800	.01308	.00000	.00000	.00000
2	6	155	.00000	.04250	1.07000	.00000	.00000	.00000
2	6	156	.00000	.04250	1.07000	.00000	.00000	.00000
1	7	13	.00580	.02650	.01090	.00000	.00000	.00000
1	7	157	.00360	.01670	.00690	.00000	.00000	.00000
1	7	158	.00100	.00890	.31703	.00000	.00000	.00000
1	7	158	.00100	.00890	.31703	.00000	.00000	.00000
1	7	28	.00170	.00750	.14200	.00000	.00000	.00000
1	7	28	.00170	.00750	.14200	.00000	.00000	.00000
1	7	32	.00180	.00670	.00340	.00000	.00000	.00000
1	7	159	.00310	.01160	.00590	.00000	.00000	.00000
2	7	160	.00000	.10000	1.00000	.00000	.00000	.00000
2	7	160	.00000	.10000	1.00000	.00000	.00000	.00000
1	8	35	.00370	.02900	.02430	.00000	.00000	.00000

1	9	10	.00340	.01590	.00670	.00000	.00000	.00000
1	9	11	.00340	.01050	.00440	.00000	.00000	.00000
1	9	11	.00340	.01050	.00440	.00000	.00000	.00000
1	9	12	.00470	.02600	.01524	.00000	.00000	.00000
1	9	161	.01980	.07080	.02840	.00000	.00000	.00000
1	9	161	.01980	.07080	.02840	.00000	.00000	.00000
1	9	13	.01010	.03670	.01450	.00000	.00000	.00000
1	9	13	.01010	.03670	.01450	.00000	.00000	.00000
1	10	40	.00610	.02810	.01220	.00000	.00000	.00000
1	11	13	.00830	.04060	.01700	.00000	.00000	.00000
1	11	14	.00250	.01270	.00520	.00000	.00000	.00000
1	11	19	.00160	.00530	.26546	.00000	.00000	.00000
1	11	21	.00220	.00690	.36660	.00000	.00000	.00000
1	11	23	.00080	.00280	.17110	.00000	.00000	.00000
1	11	24	.00130	.00470	.17560	.00000	.00000	.00000
2	11	162	.00000	.07030	1.07000	.00000	.00000	.00000
2	11	163	.00000	.03100	1.05000	.00000	.00000	.00000
1	12	164	.00690	.03610	.01905	.00000	.00000	.00000
1	13	157	.00210	.00980	.00410	.00000	.00000	.00000
1	13	14	.00740	.03450	.01450	.00000	.00000	.00000
1	13	15	.00560	.01990	.00800	.00000	.00000	.00000
1	13	15	.00560	.01990	.00800	.00000	.00000	.00000
1	14	165	.00030	.00090	.06031	.00000	.00000	.00000
1	15	16	.00200	.01850	.01560	.00000	.00000	.00000
1	15	16	.00200	.01850	.01560	.00000	.00000	.00000
1	15	17	.00040	.00310	.23320	.00000	.00000	.00000
1	15	17	.00040	.00310	.23320	.00000	.00000	.00000
1	15	154	.00640	.01960	.00740	.00000	.00000	.00000
1	15	154	.00640	.01960	.00740	.00000	.00000	.00000
2	16	166	.00000	.08470	1.07000	.00000	.00000	.00000
2	16	167	.00000	.08470	1.07000	.00000	.00000	.00000
1	17	18	.00020	.00170	.08000	.00000	.00000	.00000
1	17	18	.00020	.00170	.08000	.00000	.00000	.00000
1	17	168	.00080	.00230	.10050	.00000	.00000	.00000
1	18	169	.00030	.00180	.12780	.00000	.00000	.00000
1	18	169	.00030	.00180	.12780	.00000	.00000	.00000
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1	21	171	.00150	.00480	.24103	.00000	.00000	.00000
1	22	44	.00070	.00250	.11780	.00000	.00000	.00000
1	23	24	.00050	.00170	.10490	.00000	.00000	.00000
1	24	172	.00090	.00430	.00180	.00000	.00000	.00000
1	25	29	.00160	.00880	.16500	.00000	.00000	.00000
1	25	29	.00160	.00880	.16500	.00000	.00000	.00000
1	26	46	.00020	.00130	.10860	.00000	.00000	.00000
1	26	46	.00020	.00130	.10860	.00000	.00000	.00000
1	27	158	.00080	.00320	.19860	.00000	.00000	.00000
1	27	158	.00080	.00320	.19860	.00000	.00000	.00000
1	28	173	.00040	.00170	.10915	.00000	.00000	.00000
1	28	173	.00040	.00170	.10915	.00000	.00000	.00000
1	29	30	.00100	.00790	.00250	.00000	.00000	.00000
1	29	31	.00140	.01050	.00400	.00000	.00000	.00000
1	29	174	.00050	.00390	.24130	.00000	.00000	.00000
1	29	174	.00050	.00390	.24130	.00000	.00000	.00000
1	30	149	.00310	.02470	.01200	.00000	.00000	.00000
1	30	175	.00050	.00390	.36200	.00000	.00000	.00000
1	31	149	.00120	.00980	.00300	.00000	.00000	.00000
1	32	159	.00190	.00790	.00410	.00000	.00000	.00000
1	33	151	.00740	.03940	.00430	.00000	.00000	.00000

1	34	35	.00920	.03920	.01660	.00000	.00000	.00000
1	35	84	.01450	.06660	.02880	.00000	.00000	.00000
1	35	84	.01450	.06660	.02880	.00000	.00000	.00000
1	36	37	.00100	.01040	.17248	.00000	.00000	.00000
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2	36	38	.00000	.02050	.90000	.00000	.00000	.00000
2	36	38	.00000	.02050	.90000	.00000	.00000	.00000
1	36	54	.00190	.03280	.80427	.00000	.00000	.00000
1	36	54	.00190	.03280	.80427	.00000	.00000	.00000
1	36	69	.00450	.04750	.80933	.00000	.00000	.00000
1	36	69	.00450	.04750	.80933	.00000	.00000	.00000
2	37	39	.00000	.02050	.88000	.00000	.00000	.00000
2	37	39	.00000	.02000	.88000	.00000	.00000	.00000
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1	38	176	.00060	.00460	.00385	.00000	.00000	.00000
1	38	177	.00060	.00410	.16945	.00000	.00000	.00000
1	38	177	.00060	.00410	.16945	.00000	.00000	.00000
1	38	177	.00060	.00410	.16945	.00000	.00000	.00000
1	38	52	.00820	.06350	.05330	.00000	.00000	.00000
1	38	52	.00820	.06350	.05330	.00000	.00000	.00000
2	38	178	.00000	.10000	1.00000	.00000	.00000	.00000
2	38	178	.00000	.10000	1.00000	.00000	.00000	.00000
1	39	40	.00180	.01410	.01193	.00000	.00000	.00000
1	39	40	.00180	.01410	.01193	.00000	.00000	.00000
1	39	42	.00290	.02250	.01910	.00000	.00000	.00000
1	39	42	.00290	.02250	.01910	.00000	.00000	.00000
1	39	179	.01230	.05760	.02360	.00000	.00000	.00000
1	39	179	.01230	.05760	.02360	.00000	.00000	.00000
2	39	180	.00000	.10000	1.00000	.00000	.00000	.00000
2	39	180	.00000	.10000	1.00000	.00000	.00000	.00000
1	40	164	.00350	.01640	.00700	.00000	.00000	.00000
1	40	43	.00860	.03880	.01696	.00000	.00000	.00000
1	40	43	.00860	.03880	.01696	.00000	.00000	.00000
1	41	42	.00080	.00260	.18500	.00000	.00000	.00000
1	41	42	.00080	.00260	.18500	.00000	.00000	.00000
1	41	181	.00060	.00410	.27000	.00000	.00000	.00000
1	42	181	.00080	.00560	.42230	.00000	.00000	.00000
1	43	182	.00490	.02010	.01130	.00000	.00000	.00000
1	43	45	.00420	.02460	.01070	.00000	.00000	.00000
1	43	47	.01140	.04910	.01980	.00000	.00000	.00000
1	43	47	.01140	.04910	.01980	.00000	.00000	.00000
1	43	47	.01020	.04750	.02010	.00000	.00000	.00000
1	43	51	.00590	.02120	.00858	.00000	.00000	.00000
1	43	53	.02570	.09090	.03676	.00000	.00000	.00000
1	43	183	.02900	.24380	.09860	.00000	.00000	.00000
1	44	182	.00040	.00240	.00130	.00000	.00000	.00000
1	44	45	.00220	.01230	.00530	.00000	.00000	.00000
1	45	184	.00030	.00200	.16000	.00000	.00000	.00000
1	45	184	.00030	.00200	.16000	.00000	.00000	.00000
1	46	185	.00350	.01790	.00776	.00000	.00000	.00000
1	46	177	.00030	.00240	.17500	.00000	.00000	.00000
1	47	48	.00250	.10330	.04395	.00000	.00000	.00000
1	47	49	.01780	.07170	.03120	.00000	.00000	.00000
1	47	50	.01820	.06370	.02370	.00000	.00000	.00000
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2	47	187	.00000	.45590	1.05000	.00000	.00000	.00000
2	47	188	.00000	.18670	1.05000	.00000	.00000	.00000

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2	48	189	.00000	.35070	1.07000	.00000	.00000	.00000
2	48	190	.00000	.36680	1.07000	.00000	.00000	.00000
2	48	191	.00000	.36340	1.07000	.00000	.00000	.00000
2	48	192	.00000	.32860	1.07000	.00000	.00000	.00000
2	49	193	.00000	.32210	1.07000	.00000	.00000	.00000
2	49	194	.00000	.32310	1.07000	.00000	.00000	.00000
2	50	195	.00000	.42880	1.05000	.00000	.00000	.00000
2	50	196	.00000	.43160	1.05000	.00000	.00000	.00000
2	51	197	.00000	.57430	1.03000	.00000	.00000	.00000
2	51	198	.00000	.57520	1.03000	.00000	.00000	.00000
2	51	199	.00000	.57520	1.03000	.00000	.00000	.00000
2	51	200	.00000	.57660	1.03000	.00000	.00000	.00000
2	52	201	.00000	.04970	1.05000	.00000	.00000	.00000
2	52	202	.00000	.04970	1.05000	.00000	.00000	.00000
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1	53	203	.01230	.05790	.02399	.00000	.00000	.00000
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1	54	98	.00300	.05340	1.28264	.00000	.00000	.00000
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2	55	57	.00000	.02000	.96000	.00000	.00000	.00000
1	56	183	.00470	.02170	.00920	.00000	.00000	.00000
1	56	183	.00470	.02170	.00920	.00000	.00000	.00000
1	56	64	.01610	.07640	.03295	.00000	.00000	.00000
1	56	65	.04440	.21390	.08962	.00000	.00000	.00000
1	56	67	.00790	.06190	.04830	.00000	.00000	.00000
1	56	67	.00790	.06190	.04830	.00000	.00000	.00000
2	56	204	.00000	.10000	1.00000	.00000	.00000	.00000
1	57	58	.01850	.12320	.09525	.00000	.00000	.00000
1	57	58	.01850	.12320	.09525	.00000	.00000	.00000
1	57	61	.00590	.03990	.03130	.00000	.00000	.00000
1	57	62	.00100	.00450	.00410	.00000	.00000	.00000
1	57	62	.00100	.00450	.00410	.00000	.00000	.00000
1	57	63	.00930	.06310	.04875	.00000	.00000	.00000
2	57	205	.00000	.10000	1.00000	.00000	.00000	.00000
1	58	59	.01080	.05270	.02000	.00000	.00000	.00000
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1	58	60	.02740	.09730	.03910	.00000	.00000	.00000
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1	58	183	.01650	.05760	.02340	.00000	.00000	.00000
1	58	104	.03920	.18590	.07560	.00000	.00000	.00000
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2	58	207	.00000	.10580	1.05000	.00000	.00000	.00000
2	58	208	.00000	.09360	1.05000	.00000	.00000	.00000
2	58	209	.00000	.09360	1.05000	.00000	.00000	.00000
2	58	210	.00000	.11540	1.05000	.00000	.00000	.00000
2	58	211	.00000	.11540	1.05000	.00000	.00000	.00000
2	58	212	.00000	.11540	1.05000	.00000	.00000	.00000
1	59	104	.02860	.13450	.05140	.00000	.00000	.00000
1	60	62	.02470	.08770	.03610	.00000	.00000	.00000
1	60	62	.02470	.08770	.03610	.00000	.00000	.00000
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1	61	62	.01630	.06200	.02270	.00000	.00000	.00000
1	61	63	.00410	.02850	.01614	.00000	.00000	.00000
2	61	213	.00000	.07410	1.06000	.00000	.00000	.00000
2	61	214	.00000	.04650	1.09000	.00000	.00000	.00000

1	62	215	.03300	.10700	.00780	.00000	.00000	.00000
1	62	215	.03300	.10700	.00780	.00000	.00000	.00000
1	63	216	.02670	.12910	.05216	.00000	.00000	.00000
1	63	216	.02670	.12910	.05216	.00000	.00000	.00000
1	64	66	.03010	.14310	.06010	.00000	.00000	.00000
1	65	66	.00610	.02900	.01210	.00000	.00000	.00000
2	66	217	.00000	.09420	1.05000	.00000	.00000	.00000
2	66	218	.00000	.09420	1.05000	.00000	.00000	.00000
1	67	68	.00130	.01050	.00821	.00000	.00000	.00000
1	67	68	.00130	.01050	.00821	.00000	.00000	.00000
2	68	219	.00000	.07510	1.07000	.00000	.00000	.00000
2	68	220	.00000	.07510	1.07000	.00000	.00000	.00000
2	68	221	.00000	.07510	1.07000	.00000	.00000	.00000
2	68	222	.00000	.07510	1.07000	.00000	.00000	.00000
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1	70	71	.00040	.00770	.18740	.00000	.00000	.00000
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1	72	73	.00220	.01600	.00720	.00000	.00000	.00000
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1	72	225	.01240	.04620	.01873	.00000	.00000	.00000
1	72	78	.00740	.05860	.04920	.00000	.00000	.00000
1	72	78	.00740	.05860	.04920	.00000	.00000	.00000
1	72	84	.02990	.13870	.05840	.00000	.00000	.00000
1	72	226	.02100	.09900	.04164	.00000	.00000	.00000
1	72	104	.03450	.11500	.04620	.00000	.00000	.00000
1	72	104	.03450	.11500	.04620	.00000	.00000	.00000
2	72	227	.00000	.10000	1.00000	.00000	.00000	.00000
2	72	227	.00000	.10000	1.00000	.00000	.00000	.00000
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2	76	230	.00000	.20000	1.08000	.00000	.00000	.00000
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1	81	83	.00890	.03420	.01379	.00000	.00000	.00000
1	82	91	.03070	.11310	.04620	.00000	.00000	.00000
1	83	91	.04590	.16540	.06723	.00000	.00000	.00000
1	84	226	.01160	.05520	.02318	.00000	.00000	.00000
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1	89	94	.00800	.05770	.02540	.00000	.00000	.00000
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2	89	246	.00000	.10000	1.00000	.00000	.00000	.00000
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1	98	121	.00120	.02020	.49392	.00000	.00000	.00000
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1	100	258	.00290	.01440	.01360	.00000	.00000	.00000
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1	100	111	.00710	.05610	.04692	.00000	.00000	.00000
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1	101	260	.00370	.02040	.00890	.00000	.00000	.00000
2	101	261	.00000	.10000	1.00000	.00000	.00000	.00000
2	101	261	.00000	.10000	1.00000	.00000	.00000	.00000
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1	107	257	.00340	.01430	.00580	.00000	.00000	.00000
1	107	265	.00570	.02010	.00810	.00000	.00000	.00000
1	107	111	.00840	.03960	.01656	.00000	.00000	.00000
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1	107	127	.03260	.13500	.00240	.00000	.00000	.00000
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1	108	258	.00630	.04240	.01330	.00000	.00000	.00000
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1	109	258	.00080	.00560	.22715	.00000	.00000	.00000
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1	112	266	.04250	.17740	.07650	.00000	.00000	.00000
1	113	266	.01260	.04480	.01865	.00000	.00000	.00000
1	113	260	.00150	.00730	.00290	.00000	.00000	.00000
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1	114	115	.00120	.01230	.21300	.00000	.00000	.00000
1	114	115	.00120	.01230	.21300	.00000	.00000	.00000
1	114	119	.00070	.00700	.12130	.00000	.00000	.00000

1	114	119	.00070	.00700	.12130	.00000	.00000	.00000
2	114	122	.00000	.02100	.98000	.00000	.00000	.00000
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1	115	117	.00030	.00520	.12760	.00000	.00000	.00000
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2	115	123	.00000	.02050	.95000	.00000	.00000	.00000
2	115	123	.00000	.02050	.95000	.00000	.00000	.00000
2	115	123	.00000	.02050	.95000	.00000	.00000	.00000
1	116	118	.00090	.01570	.38390	.00000	.00000	.00000
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2	120	273	.00000	.03050	1.05000	.00000	.00000	.00000
2	121	274	.00000	.01390	1.05000	.00000	.00000	.00000
2	121	275	.00000	.01390	1.05000	.00000	.00000	.00000
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1	122	276	.01330	.04720	.01917	.00000	.00000	.00000
1	122	277	.01890	.08930	.03730	.00000	.00000	.00000
1	122	138	.00240	.01840	.01560	.00000	.00000	.00000
1	122	278	.00130	.00690	.00290	.00000	.00000	.00000
1	122	278	.00130	.00690	.00290	.00000	.00000	.00000
1	122	139	.00290	.02130	.00920	.00000	.00000	.00000
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1	122	140	.00180	.01380	.01110	.00000	.00000	.00000
1	122	140	.00180	.01390	.01170	.00000	.00000	.00000
1	122	279	.00130	.01090	.00650	.00000	.00000	.00000
2	122	280	.00000	.10000	1.00000	.00000	.00000	.00000
2	122	280	.00000	.10000	1.00000	.00000	.00000	.00000
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1	123	281	.01510	.05370	.01630	.00000	.00000	.00000
1	123	130	.00670	.02380	.00960	.00000	.00000	.00000
1	123	131	.00650	.02280	.00920	.00000	.00000	.00000
1	123	133	.01030	.03620	.00270	.00000	.00000	.00000
1	123	133	.01030	.03620	.00270	.00000	.00000	.00000
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1	123	136	.00580	.02030	.00823	.00000	.00000	.00000
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1	123	277	.00820	.03890	.01620	.00000	.00000	.00000
1	123	142	.00790	.06140	.05292	.00000	.00000	.00000
1	123	142	.00790	.06140	.05292	.00000	.00000	.00000
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2	123	282	.00000	.10000	1.00000	.00000	.00000	.00000
1	124	283	.00450	.02680	.01120	.00000	.00000	.00000
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1	124	284	.00370	.02470	.01950	.00000	.00000	.00000
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1	124	128	.01890	.08810	.03726	.00000	.00000	.00000
1	124	128	.01890	.08810	.03726	.00000	.00000	.00000
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1	126	141	.02620	.12160	.05110	.00000	.00000	.00000
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1	127	283	.00850	.03610	.01490	.00000	.00000	.00000
1	127	283	.00850	.03610	.01490	.00000	.00000	.00000
1	127	281	.01510	.05370	.01630	.00000	.00000	.00000
1	128	129	.00300	.01380	.00585	.00000	.00000	.00000
1	128	252	.02280	.11400	.04737	.00000	.00000	.00000
1	129	289	.02410	.11220	.04706	.00000	.00000	.00000
1	130	132	.00690	.02720	.01170	.00000	.00000	.00000
1	131	133	.00380	.01330	.00540	.00000	.00000	.00000
1	132	133	.00230	.00840	.00330	.00000	.00000	.00000
1	133	290	.00110	.00560	.04535	.00000	.00000	.00000
1	133	291	.00250	.00690	.02360	.00000	.00000	.00000
2	133	292	.00000	.10530	1.05000	.00000	.00000	.00000
2	133	293	.00000	.10530	1.05000	.00000	.00000	.00000
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1	135	137	.00110	.00530	.05274	.00000	.00000	.00000
1	135	137	.00110	.00530	.05487	.00000	.00000	.00000
1	135	296	.00040	.00270	.19200	.00000	.00000	.00000
1	135	296	.00040	.00270	.19200	.00000	.00000	.00000
1	136	137	.00480	.01620	.00656	.00000	.00000	.00000
1	136	137	.00480	.01620	.00656	.00000	.00000	.00000
1	136	276	.02450	.08660	.03521	.00000	.00000	.00000
1	137	286	.00080	.00600	.16690	.00000	.00000	.00000
1	137	286	.00080	.00600	.15000	.00000	.00000	.00000
1	138	297	.00830	.04030	.01630	.00000	.00000	.00000
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1	138	140	.00370	.02880	.02580	.00000	.00000	.00000
2	139	298	.00000	.04650	1.06000	.00000	.00000	.00000
2	139	299	.00000	.04200	1.07000	.00000	.00000	.00000
1	140	279	.00220	.01740	.01459	.00000	.00000	.00000
2	140	300	.00000	.03960	1.06000	.00000	.00000	.00000
2	140	301	.00000	.03960	1.06000	.00000	.00000	.00000
2	140	302	.00000	.03960	1.06000	.00000	.00000	.00000
2	140	303	.00000	.09600	1.06000	.00000	.00000	.00000
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1	141	288	.01050	.04890	.02683	.00000	.00000	.00000
2	142	305	.00000	.02860	1.05000	.00000	.00000	.00000
2	142	306	.00000	.02860	1.05000	.00000	.00000	.00000

Generator and Load Pattern

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  38  171   37  163   1.0000    .0000    .0000   1.0000
   1  155    2.0000   1.6000
   1  156    2.0000   1.6000
   1  143    2.7000   2.2700
   1  163    2.5000   1.0000
   1  145    2.5000   1.7500
   1  146    2.5000   1.7500
   1  197     .2000    .3300
   1  198     .2000    .3300
   1  186     .2000    .0900
   1  187     .2000    .0900
   1  189     .0500    .1300
   1  190     .0500    .1300
   1  191     .0500    .1300
   1  192     .0500    .1300
   1  193     .2500    .1300
   1  201    1.5000    .4000
   1  195     .2000    .1000
   1  214    1.8000   1.2400
   1  219     .5000    .7000
   1  220     .5000    .7000
   1  217     .8000    .4500
   1  223    5.0000   2.8000
   1  224    5.0000   2.8000
   1  229     .4000    .2100
   1  233    1.8000   1.2400
   1  253    2.0000   1.7400
   1  243    9.5000   4.5000
   1  244    9.5000   4.5000
   1  255    6.7900   4.2100
   1  267    5.0000   3.0000
   1  268    5.0000   3.0000
   1  269    5.8700   3.6400
   1  270    6.5000   4.0300
   1  274    9.5000   5.5000
   1  275    9.5000   5.5000
   1  272    2.8400   2.4800
   1  305    2.5000   2.1000
   1  306    2.5000   2.1000
   5    .0200    .0000
   6   1.2800   1.1600
   7    .7800    .2600
   9   1.0000   -.1400
  10    .2800    .1300
  11    .3700    .1000
  12    .3100    .0900
 161    .3100    .0900
  13   2.9100   1.6900
 157   1.7200    .8200
  14    .8500    .2700
  15   1.9300    .7300
  17    .5300    .1200
 154    .9200    .1900
  18    .8900    .2400
  19    .9100    .2800
  20    .7100    .2300
  21    .3100    .1000
  22    .5000    .1900
```

23	.5600	.1600
24	.7000	.2900
172	.1900	.1000
25	.5300	.1900
26	.4600	.2300
27	.4100	.1600
158	1.1000	.4400
28	1.2000	.6000
29	1.1800	.1700
30	.6600	.2900
31	.1500	.0600
149	.7400	.3000
32	1.0800	.3200
159	.5100	.2800
150	1.2800	.6200
33	1.1300	.5900
151	1.3600	.5400
34	.8600	.4400
35	.6500	.2700
152	1.2200	.4900
38	.5200	.1700
40	.9100	.5900
164	.5600	.2000
41	.7000	.4100
42	.7000	.3800
181	.4600	.1600
179	.5800	.2300
43	.6500	.2400
44	.7400	.3400
182	.7800	.1700
45	.5100	.2100
184	.8000	.3700
46	.4100	.1200
185	.9700	.3800
177	.4300	.1500
47	.0300	.0100
48	.0300	.0100
49	.0600	.0100
53	1.3600	.3200
56	.9300	.4600
57	1.8700	.7300
58	.3900	.0600
59	.4600	.1200
60	1.0400	-.0100
62	.8400	.3400
63	.2300	.1200
216	.1000	-.0800
183	.2300	-.0400
64	.5000	.1700
65	.2300	.1000
67	.2900	.1200
72	.1700	.0600
73	.5200	.1900
225	.7400	.3700
74	.4900	.2300
75	.2400	.1200
77	1.3200	.4900
228	.4800	.2300
78	.1600	.0500

80	.1900	-.0500
232	.1700	.0600
231	.1300	.0100
81	1.3500	.2600
235	.8400	.2800
82	.3800	.0900
83	.2800	.0600
84	1.7100	.6100
226	.2300	.1200
89	.2200	.0900
91	.5600	.1300
92	.6200	.1000
93	.4600	-.1800
250	.3100	-.0300
251	.2700	-.1500
94	.5900	.2600
248	.3200	.0400
95	.1600	.0300
96	1.7100	.4300
249	.2200	.0900
102	.5300	.2300
103	1.6400	.6400
262	.2100	.0900
104	.4600	.1000
105	.4800	.1300
107	.9200	.1500
256	1.0300	.4800
257	.7700	.3000
265	.3700	.1000
108	.8200	.0300
109	.5800	.2300
258	1.4400	.5200
110	.6700	.2300
111	.3600	.0900
112	.2300	.0600
113	1.3900	.3500
266	.3600	.0200
260	.2300	.2300
122	.2700	.0900
123	.3100	.0600
124	.5200	.1700
127	.4100	-.2000
283	1.5700	.2800
284	2.2700	.4100
128	.5200	-.0400
129	.3000	.0800
289	.1200	-.0900
281	.1500	.0300
130	1.2100	.5000
131	1.3300	.6400
132	.5100	.2300
133	.5900	.2200
290	.4600	.1200
291	.7200	.1900
134	.8100	.3500
135	.4500	.1200
136	.9500	.2700
137	1.9000	.4900
296	.3000	.0500

```
  276   .2100   .1000
  286   .4200   .1900
  277   .6700   .2200
  138  1.8000  1.0500
  297   .3700   .1200
  278  1.5300   .6500
  140   .7300   .4100
  279  1.0400   .4100
  141   .3600   .1500
  288   .3100   .1200
  155   .1000   .0500
  156   .1000   .0500
  143   .1000   .0500
  163   .1100   .0500
  145   .1100   .0500
  146   .1100   .0500
  214   .1400   .0700
  219   .0100   .0000
  220   .0100   .0000
  217   .0100   .0000
  223   .3000   .1500
  224   .3000   .1500
  233   .2000   .1000
  253   .2500   .1200
  243   .6500   .3000
  244   .6500   .3000
  255   .4400   .2200
  267   .2700   .1300
  268   .2700   .1300
  269   .3700   .1800
  270   .4200   .2100
  274   .6500   .3200
  275   .6500   .3200
  272   .2000   .1200
155.0000   1.0000
156.0000   1.0000
143.0000   1.0000
145.0000   1.0000
146.0000   1.0000
197.0000   1.0000
198.0000   1.0000
186.0000   1.0000
187.0000   1.0000
189.0000   1.0000
190.0000   1.0000
191.0000   1.0000
192.0000   1.0000
193.0000   1.0000
201.0000   1.0000
195.0000   1.0000
214.0000   1.0000
219.0000   1.0000
220.0000   1.0000
217.0000   1.0000
223.0000   1.0000
224.0000   1.0000
229.0000   1.0000
233.0000   1.0000
253.0000   1.0000
```

243.0000	1.0000
244.0000	1.0000
255.0000	1.0000
267.0000	1.0000
268.0000	1.0000
269.0000	1.0000
270.0000	1.0000
274.0000	1.0000
275.0000	1.0000
272.0000	1.0000
305.0000	1.0000
306.0000	1.0000

APPENDIX D: SINGULAR VALUE DECOMPOSITION [162, 163]

The use of the singularity of power flow Jacobian matrix as an indictor of steady-state stability was first proposed by Venikov et al [162], where the sign of the determinant of J was used to determine whether the studied operating point was stable or not. The minimum singular value of power flow Jacobian matrix J, has been proposed as a static voltage stability index, in which the minimum singular value is used to indicate the distance between the studies operating point and the static voltage stability limit.

The singular value decomposition is an important and practically useful orthogonal decomposition method used for matrix computations. If matrix A is an n by n quadratic real matrix, then the singular value decomposition is given by:

$$A = U\sum V^T = \sum \sigma_i u_i v_i^T \qquad \text{(D-1)}$$

where U and V are n by n orthonormal matrices, the singular vectors u_i and v_i are columns of matrices U and V respectively.

If the matrix A has rank r ($r <= n$) its singular value are the square roots of the r positive eigenvalue of A^TA, which also are r positive eigenvalue of A^TA. The smallest singular value of the matrix A is a measure of the distance, in which l_2-norm, between A and the set of all rank-deficient matrices.

The minimum singular value, is a measure of how close to singularity the power flow Jacobian matrix is. If the minimum singular value is equal to zero, the studied matrix is singular and no power flow solution can be obtained. The singularity of the Jacobian matrix corresponds to that the inverse of the matrix does not exist. This can be interpreted as an infinite sensitivity of power flow solution to perturbations in the parameters values. At the point where several branches of equilibria may come together and the studies system will experience a qualitative change in the structure of the solutions due to a change in the parameters values. In conclusion, the smallest singular value is an indicator of proximity to the steady-state stability limit. In the thesis, it is used to compare the results obtained by the proposed algorithm.