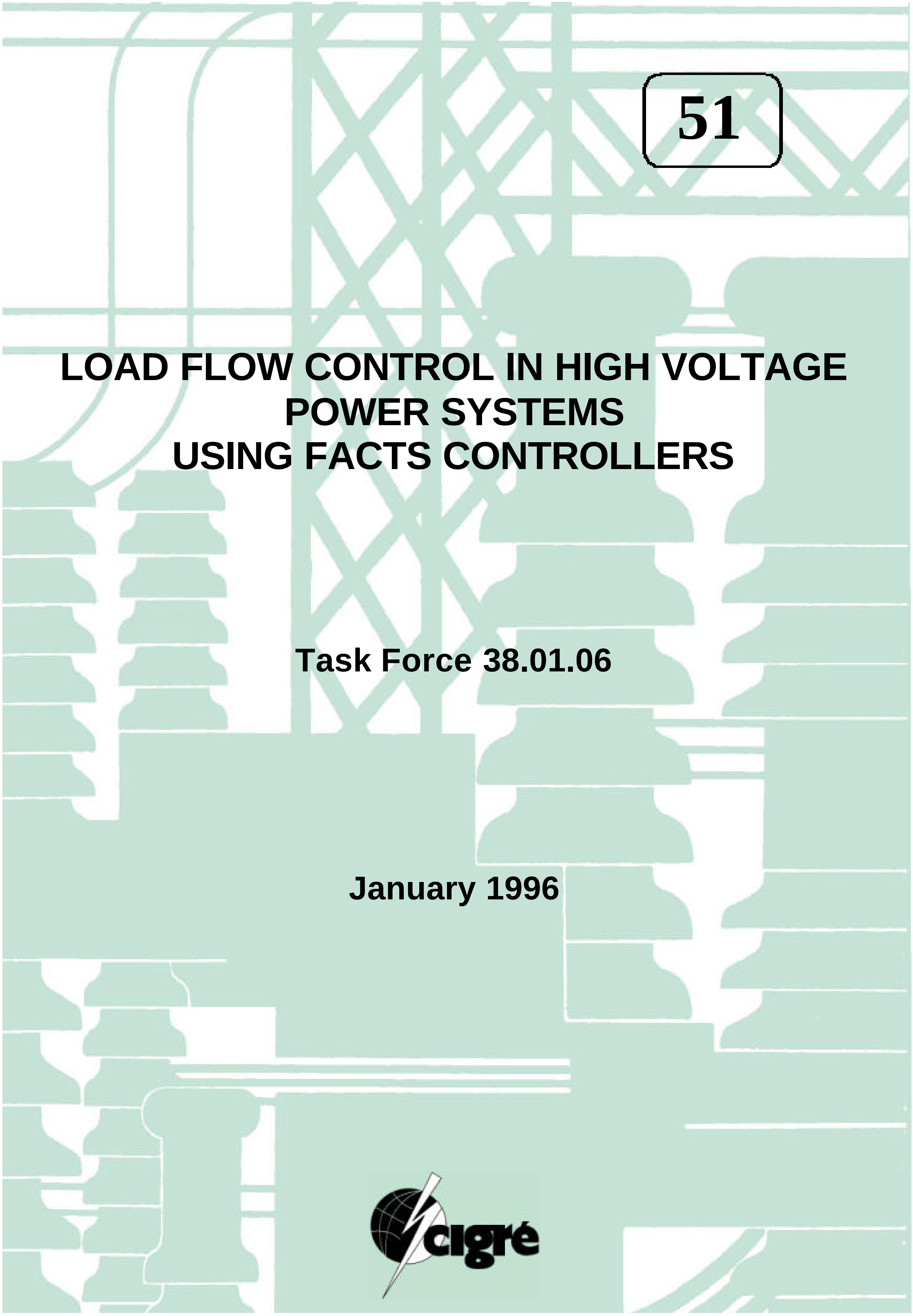

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LOAD FLOW CONTROL IN HIGH VOLTAGE POWER SYSTEMS USING FACTS CONTROLLERS

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1. Introduction

CIGRE Study Committee 38 (System Analysis) established Task Force 38-01-06 on Load Flow Control to investigate the use of FACTS-Controllers in high voltage systems and to prepare a guideline document which can be used by utility planning engineers. This document is intended to give an overview of the impact of different FACTS-controllers on power system and to present examples of use of such equipment in power systems. The load flow control in steady state conditions by switchable elements follows in general the same basic principles as for transient conditions. Their use depends on the required speed of response and frequency of utilisation.

The Task Force expects that this document will widen the understanding of the scope of possible FACTS-applications and their use in improving system operation.

Large interconnected systems tend to develop into heavy loaded systems, especially if new lines can not be built because of lack of right-of-ways. Furthermore, the location for any new generation is often remote from the load and the system takes on the task of transmitting power over longer distances. Due to deregulation in the electric power industry the requirement can arise to transmit power through given corridors. In some countries with remote power sources the main problem results from the requirement to transmit power over long distances through weak transmission systems leading to insufficient power quality. Problems resulting from above mentioned development may be, at least partly, economically improved by the use of Flexible AC Transmission System (FACTS) controllers.

The rapid development of power electronics in the last two decades has made it possible to design power electronic equipment of high rating for high voltage systems. Due to the fast control abilities of this equipment the operating conditions can be controlled in the system. This equipment is known as FACTS-Controllers. The first FACTS-Controllers applied in system were Static Var Compensators (SVC), about two decades ago. In the meantime it has become a conventional technique. Recently thyristor controlled series compensation has been introduced. The development of Turn Off devices (e.g. GTO, IGBT, MCT ...) for larger ratings makes it possible to build new improved and sophisticated FACTS controllers which are at present in the design or prototype stage. An overview of the FACTS controllers and FACTS equipment for special applications is given in [1].

The FACTS devices discussed in this report are listed in the Table below

Static Var Compensator (SVC)
Static Var Generator (SVG or STATCOM)
Controlled Series Compensation (CSC)
GTO controlled Series Compensation (GTO-CSC)
Phase Shifting Transformer (PST)
Unified Power Flow Controller (UPFC)
Interphase Power Controller (IPC)

The above acronyms for FACTS-controllers are consistent with CIGRE and IEEE working groups proposals [1]. Glossary from the report of these working groups (IEEE catalog number 95 TP 108) is given in the appendix. In this report for Static Synchronous Condenser (STATCOM) the term Static Var Generator (SVG) is also used. Instead of Static Synchronous Series Compensator the term Controlled series Compensator with GTO Converter (GTO-CSC) is used. Here also two kinds of Phase Shifting Transformers (PST) are considered i.e. Phase Angle Regulator (PAR) and Quadrature Boosting Transformer (QBT).

Interphase Power Controller (IPC) is discussed also as this device can influence power flow using resonant circuits adjustable by switching actions.

As mentioned above the SVC is a well established technique. Small rating SVGs have been in operation in industrial systems for several years. Larger rating prototypes have also been put into operation. Two TCSC schemes have operated successfully for some years. The GTO-CSC, thyristor controlled PST, and UPFC are in development phase at present. It can be expected that prototypes will be built when their feasibility has be proved. An IPC prototype also can be expected to be built and commissioned soon.

2. System Requirements for Load Flow

AC systems developed during decades mainly in two directions. In regions with high population density and where it was possible to build power stations close to the demand centres, power systems grew into meshed networks, which were later interconnected to become large meshed systems. In regions where bulk power had to be transmitted from remote power sources to demand centres long distance transmission systems using the highest voltage levels were developed.

It became difficult to build new lines because of lack in right of way and the location of new generation has often been at some distance from the demand. The need for increases in network transmission capacity has therefore grown in recent years. Due to deregulation in the electric power industry, the need to transport power between partners through defined line corridors without involving other partners in the system is expected to play an important role in the future.

The increased loading of ac systems leads to technical problems which can degrade the quality of energy delivery and endanger the reliability of the system. The technical and optimisation problems in systems can be solved by FACTS controllers and under steady state conditions also by switchable elements. Regarding the speed of response of FACTS controllers following three levels can be defined.

1) Steady state load flow control. The response time of the control can be in the range of minutes. It can normally be done by switching of reactive power elements or even by rescheduling of the generation.

2) Load flow control during the transition between different operating conditions in the system and possible overload of equipment by outages requests response times in the range of seconds. For such cases power electronic equipment is necessary, only in a simple case can switchable elements be used.

3) Load flow control during dynamic and transient conditions needs fast control with response times below 100 ms. This response can be achieved only by FACTS devices using power electronic equipment supported by sophisticated control.

Overload of equipment and lines at outages. During normal (system intact) operation transmission lines and other network equipment are loaded at typically 1/3 to 1/2 of their thermal limit. During outages conditions, however, some of the elements in the system can be stressed to their thermal or short-time overload rating limit. A cascade trip of further system elements can result which can endanger the operation of the total system. Normally the load flow control needed to avoid this problem need not be very fast-acting as the thermal time constant of system elements is in the range of minutes, depending, however, also on the protection setting.

Although with slow control it is also possible to direct power flow through a given corridor, nevertheless, using power electronic controlled equipment to adjust system parameters is much more effective. This is also important in cases when at outages or restructuring of the system unacceptable voltage conditions could occur which need fast response which is only possible by power electronic equipment.

A further advantage of power electronic equipment for load flow control in steady state conditions is the unlimited number of operations compared to the equipment using switches.

Voltage stability. With heavy loaded systems or under system outage conditions, voltage instability can occur. This can be typically experienced when the reactive power margins are limited or the transmission distance is high. The speed of the phenomenon depends on the load characteristics and controls (tap changer, load shedding, etc.). The problem can be solved by effective shunt or adjustable series compensation. However, reliable detection of the problem is required.

Transient Stability. It is mostly the limiting factor for power transmission over long distances and with relatively weak post fault system interconnections. To avoid stability problems a fast power flow control within the first electromechanical swing of the generators is required. This can be achieved by different means as voltage control, adjustment of transmission impedance and phase angle control. The impact of different means depends upon the location of the equipment and system configuration.

Oscillation damping. In interconnected and more complex transmission networks it is not the first swing (transient) stability but oscillatory stability which is the limiting factor. Power System Stabilisers (PSS) can be effective but often may not be sufficient to damp such oscillations. Additional means are required which produce damping by fast power flow control using similar techniques as for the first swing stability enhancement, i.e. voltage, impedance or phase angle control.

Limitation of short circuit capacity. In certain system conditions with increasing interconnection the short circuit capacity can exceed the design values. Fault Current may be limited by some FACTS-elements e.g. Thyristor Controlled Series Reactance (TCSR) or by IPC in which the short-circuit capacity limitation is inherent.

Idea of FACTS

As indicated a solution for the above discussed problems could be the Flexible AC Transmission System (FACTS) [2]. The advantage of this technique is that equipment can be designed according to the requirements of the system.

The idea of FACTS is explained in Fig. 2.1 which shows a schematic diagram of an AC interconnection between two systems. The active power transmitted between the systems is defined by the given equation where U_1 and U_2 are the voltages at both ends of the transmission, X is the equivalent impedance of the transmission and $\delta_1 - \delta_2$ is the phase angle difference between both systems.

From the equation in Fig. 2.1 it is evident that the transmitted power is influenced by three parameters: voltage, impedance and voltage angle difference. FACTS devices (in Fig. 2.1 examples of FACTS controller influencing different system parameters are given) can influence one or more of these parameters, and thereby influence power flow.

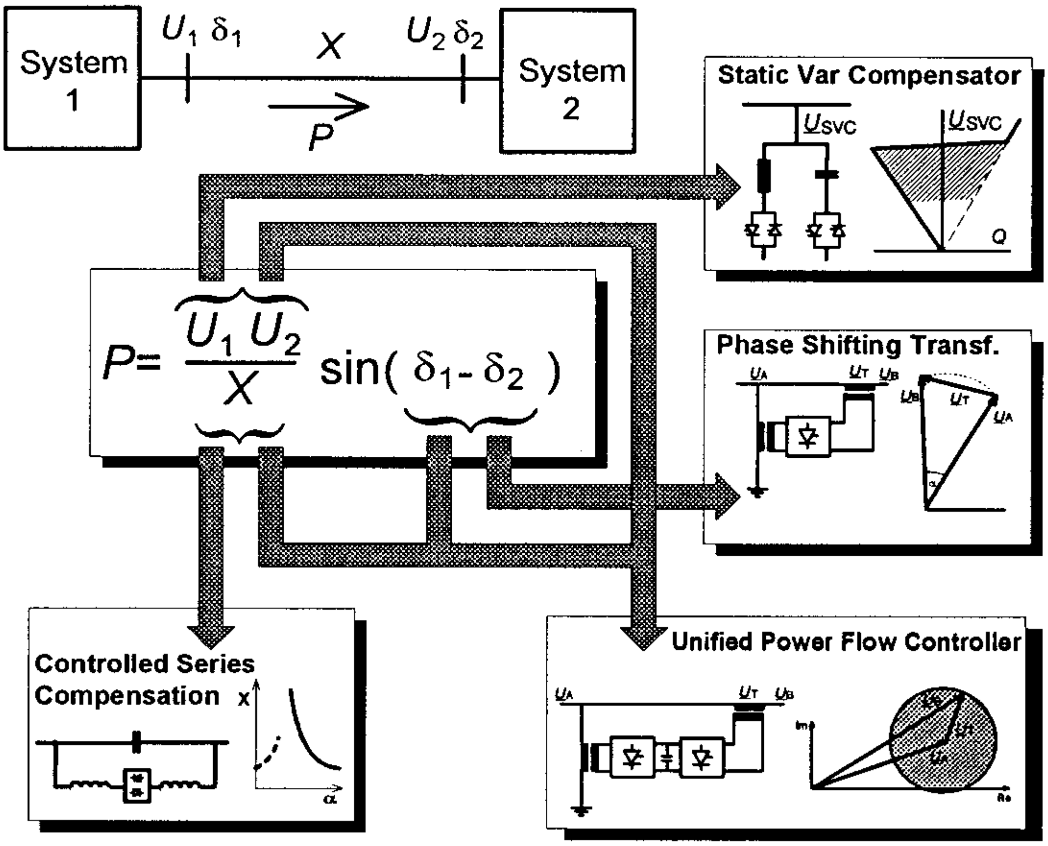


Figure 2.1: Power flow control and stability improvement in AC systems

3. FACTS Controllers

Initially in this chapter basic operating principles will be discussed which illustrates the physical background of FACTS controller and the different impacts on the system that such controllers can have depending on the location of the equipment and the system configuration.

In the second part of the chapter the operating diagrams of FACTS controllers is presented.

3.1 Basic Operating Principles

FACTS controllers are devices without any inherent real power generating capability. Examples of this type of equipment are reactive power compensators and phase-shifters. In section 3.1.1 the underlying physical principles of this class of equipment are discussed. The fundamental differences between equipment that operates by shunt current injection and by series voltage insertion is then discussed briefly in section 3.1.2 and respective effects on system characteristics in section 3.1.3. The concept of Power Flow Control can be applied in many situations. In section 3.2 an attempt is made to list a number of idealised typical applications.

3.1.1 Physical Principles

The equipment used for power flow control is based on devices using different physical principles. Three different physical principles can be distinguished:

Energy storage elements

The classic passive linear reactive power elements, i.e. inductors and capacitors, are physically energy storage elements. When operating they accumulate energy from the line during a quarter of a cycle and return it back during the following quarter cycle. A fixed relation exists between the maximum energy storage capability W_{max} of these elements and their rating as expressed in Mvar:

$$W_{max} = \frac{Q_{rated}}{\omega_N}$$

where ω_N is its rated angular frequency. It can be concluded that the energy storage capability corresponds to rated power during $1/\omega_N$ seconds, i.e. 3.18 ms (50 Hz) or 2.65 ms (60 Hz).

Separate elements are provided in each phase of the three-phase system and the energy in a specific element can only interact with a given phase. Therefore if intervention should be possible in any arbitrary phase, sufficient energy storage capability must exist in all phases.

Power redistribution by transformer action

The phase-shifting transformer is an example of the second principle, which involves power redistribution within the three-phase configuration. The ideal transformer does not store any energy, but maintains an instantaneous balance between power input and output on its primary and secondary windings. The stored energy in the real transformer actually reflects energy that is bound in its leakage fields and shows up as internal reactive power consumption.

Power redistribution using power electronics

Power electronics devices having a turn-off capability can perform fast repetitive switching in order to redistribute instantaneous power among the phases within the three-phase system. In this way reactive power can be generated or consumed almost without the use of passive reactive elements. During symmetric three-phase conditions the required capacity of the energy storing elements reduces to time intervals that are inverse of the total switching frequency. The total switching frequency in the three-phase system ranges from 300/360 Hz in the six-pulse bridge using fundamental switching frequency (50/60 Hz) and upwards to several kHz for Pulse Width Modulated (PWM) converters. This means that the need for bulky energy-storing passive elements can be substantially reduced. However it should also be considered that under unsymmetric conditions and fault conditions in the network an energy pulsation between the converter and the network at twice the rated frequency of the network occurs and means for energy storage must be provided. Equipment based on voltage source converter (VSC) technology uses the DC capacitor bank for energy storage. If energy storage is required for more than a few ms the rating of the DC link capacitor would be substantial or other means may be required to deal with the energy pulsation in the compensator (e.g. overvoltage chopper).

3.1.2 Controlled Variables

Power flow controllers can utilise one or more of the physical principles above. Depending on their construction and their operating mode, they can be visualised as a controllable voltage source in series with the line, as a controllable current injected in shunt or as a voltage-dependent current source.

Shunt current injection

Shunt devices basically impacts on the voltage at the point of connection. Shunt devices connected to stiff nodes (voltage controlled nodes) in the network have no impact on the power flow of the connected transmission lines. When connected to weak nodes in the system, e.g. in the midpoint or in the receiving end of a long transmission line, however the power flow can be influenced substantially by the change of voltage that is caused by the shunt controller.

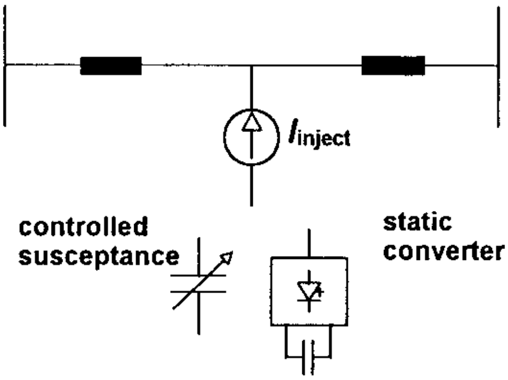


Figure 3.1: Controlled current injection in shunt

For protection purposes shunt devices are designed to limit the injected current by controller action to a certain level depending on their rating.

Controllable voltage in series with the line

A controllable voltage in series with the line can be provided by a voltage source e.g. from a power electronic converter and inserted either directly or by use of a booster transformer. It may also be created by the natural voltage drop caused by the line current across a controllable impedance element. The impact of the inserted voltage on the power flow in the system is of course independent of how the voltage is created. If the inserted voltage is controlled so that it becomes proportional to the line current it is said to be of 'impedance control' type.

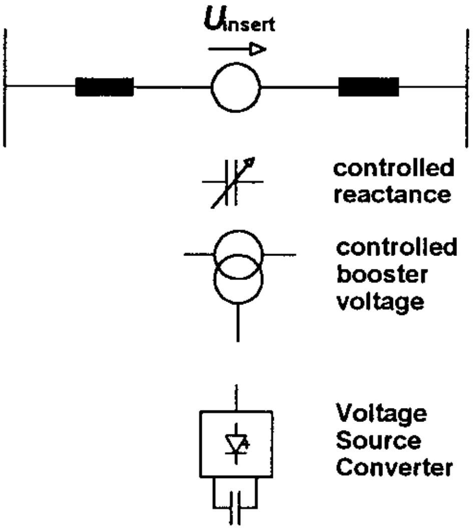


Figure 3.2: Controlled voltage in series with the line.

The insertion of a controllable voltage in series with the transmission line directly impacts on the power flow of the line. The controlled voltage is added vectorially to the driving emf that causes current to flow, i.e. the difference between the terminal voltages of the line. This makes the controlled inserted series voltage a very effective means for power flow control.

Normally the controllable voltage that can be handled by the controller is limited to a fraction of the rated voltage of the system. Therefore it can not substantially reduce the short circuit current in the line. The series controller must be designed to handle the maximum current occurring in the line during all operating conditions or, if not designed to operate during faults, bypass means must be provided.

Voltage-dependent current sources

New power flow controllers under development insert, in series with the line, energy storage elements forming a parallel resonant circuit tuned to the fundamental frequency of the network. Power flow is controlled by interphase power redistribution using phase-shifting transformers. To the network the controller appears as a pair of back-to-back voltage-dependent current sources as shown in figure 3.3.

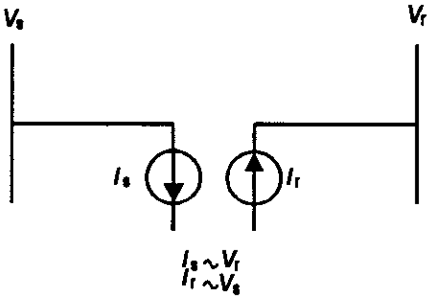


Figure 3.3: Voltage-dependent current sources

3.1.3 Impact of Controller Type and Location

The efficiency of the power flow control depends on the type of controller and on its location in the network.

Impact of controller location

It is obvious from the equivalent circuit that the location of a controller that operates in series with the line plays a minor role. From a power flow control standpoint the controller can be freely located anywhere along the transmission line in question.

The shunt device operates by change of voltage and has its maximum impact on power flow if located at the point of the transmission line where the voltage is weakest. The location of this equipment therefore has a significant impact on power flow control performance.

The voltage-dependent current source behaves similar to series devices but decouples the two sides from the point of view of reactive power flow and allow independent var management.

Differences between series and shunt connected devices with respect to the load voltage characteristics

When power flow control is executed by shunt current injection, the control action is an indirect effect of voltage change. Therefore the load characteristics with respect to voltage and the generator voltage control has a substantial impact on the control performance. Figure 3.4 shows a case where the controlled shunt injection is located in the receiving end of a transmission line. The change in active power flow from the local generation (ΔP_{source}) may be positive or negative depending on whether the change in terminal voltage causes a power change in the load (ΔP_{load}) that dominates over the change in line power transfer (ΔP_{line}) or vice versa.

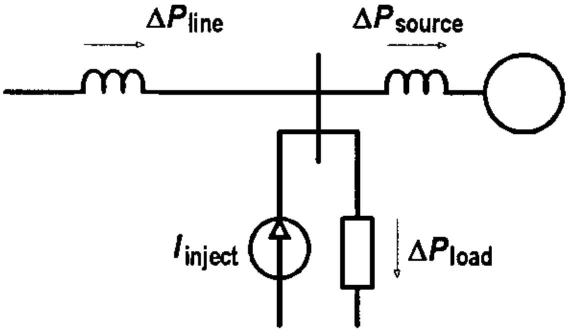


Figure 3.4: Shunt current injection in receiving end of a transmission line

On the other hand when power flow control is based on insertion of controlled voltage in series with the line the voltage dependence of the loads becomes uncritical. The reason for this is that voltage change in the terminal nodes caused by power flow control actions by series devices is small ($\Delta P_{load} \approx 0$) if the nodes are not very weak.

Efficiency of active power flow control

A first idea of equipment rating can be obtained by simply defining the rating of the equipment as

$S_{series} = U_{insert} * I_{line}$ for a series device

and

$S_{shunt} = I_{inject} * U_{line}$ for a shunt device

It can be shown, from comparison of simple models such as in figures 3.18 and 3.20 of section 3.4, that devices based on series voltage insertion have a higher impact, in MW change in line per inserted Mvar, than shunt-connected devices. For load angles around $\delta=30°$ the theoretical difference would be about one order of magnitude. In practical transmission systems with typical source impedances the difference would be lower; the example in section 4.6 indicates a rating ratio around 3.

3.2 Power Flow Control in the System

Power flow control equipment has different objectives depending on the type of transmission system in which it is installed. The requirement for power flow control differs between a long-distance power transmission installation and in a meshed network. Another dissimilarity exists for steady-state application or transient power flow control.

In steady state conditions the total power flow on all lines that connect two power systems is determined by the unbalance between power production and load demand in the individual systems. The transmission system can only influence the distribution of this total power flow among the different power transmission facilities connecting the systems. During transients, on the other hand, power flow control equipment can also have an impact on the total power exchange between the systems by consuming some of the kinetic energy in one system transporting it to the other system. Some typical situations are outlined in the following.

3.2.1 Power Flow Control in Long-Distance Transmission Systems

Long-distance transmission operate with a substantial phase angle difference between the sending and the receiving end. First swing and dynamic stability often are of concern as electromechanical power oscillations with low damping can occur after system faults. Damping can be provided by power control devices that modulate the power flow in the line so that the power transfer increases whenever the sending end frequency exceeds that of the receiving end. Such power modulation can be achieved by apparatus of both series-voltage and shunt-current type.

Long-distance power transmission also involves large amounts of reactive power that is generated/consumed by the lines. Unbalance in the reactive power management results in voltage deviations from the rated value. Series-compensation with fixed series capacitors has been used for long time to compensate the reactive power consumption in the lines thereby decreasing the angular difference between sending and receiving end voltages. Additional control of voltage and active power flow can be provided by controlled shunt-current or series-voltage injection.

3.2.2 Power Flow Control on One Line Carrying a Fraction of the Total Power Transmission in Power Corridor

Some portions of the network connect main power production facilities with main loading areas (Fig. 3.5). Several transmission facilities, possibly with different voltage levels, run in parallel between these areas. It might be of interest to control the power flow on certain of these lines. Typically the purpose is to remove a constraint that limits the possible power transfer between the systems and hence to increase the utilisation of the transmission assets..

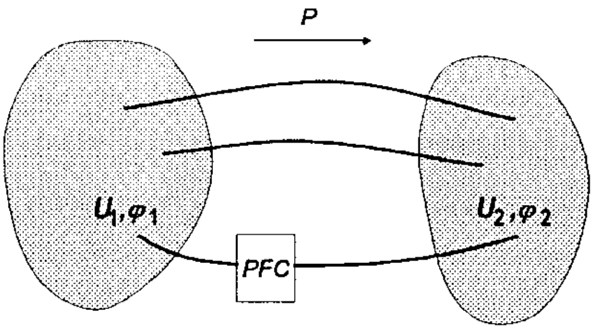


Figure 3.5: Load flow control of a single line in power flow corridor. (PFC=Power Flow Controller)

In this case power flow direction is defined and the phase angle difference between the sending end and the receiving end are only marginally influenced by the power flow on the controlled transmission line.

Under these circumstances it is obvious that the change of real power flow that is obtained due to an inserted voltage in series with the line will be independent of whether the source is a CSC, PST, IPC or UPFC. The rating of each of the devices will become very close. For power flow control normally the rating of a shunt device (SVC) would be substantially larger. Specific reasons may motivate its use, e.g. when voltage control is also required.

3.2.3 Power Flow Control to Share Load Between Main Transmission Facilities.

Power flow control facilities in transmission systems connecting a generating centre with a load area can be installed to control the load sharing on the transmission lines (Fig. 3.6). The purpose in this case may be to optimise the power flow pattern for minimum transmission losses and/or to improve the loadability of the transmission facilities between the systems during contingencies by using a power flow controller in the loop.

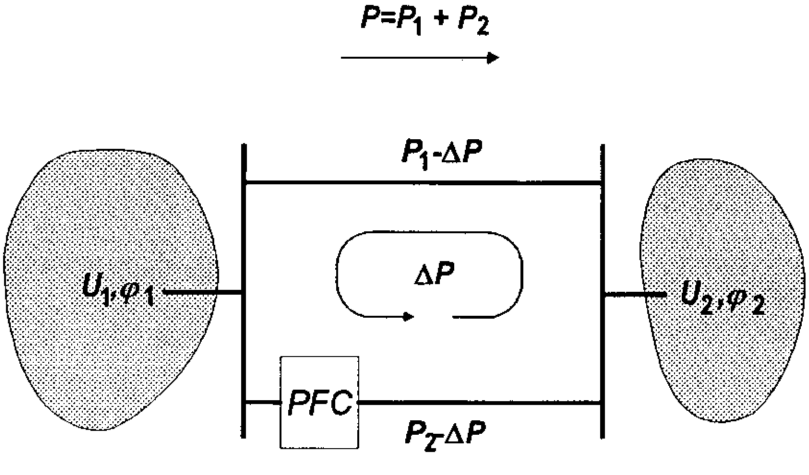


Figure 3.6: Load sharing control in a power flow corridor.

Similar ratings will be obtained for different equipment that injects voltage in series with the line, whether it creates a voltage by a change of inserted reactance or if a corresponding transformer emf is being inserted. The devices that exclusively vary either one of the reactive series voltage or the reactive shunt current injection can only be used to control one parameter e.g. the active power flow. In that case the reactive power flow will take a value that can not be controlled. Devices like UPFC that can control both the inserted voltage amplitude and its phase angle can impact both active and reactive power flow simultaneously. Devices that have capability to produce reactive power (CSC, SVC, IPC, UPFC) may be favoured if the power flow control device is used to increase the loadability of the remaining lines during contingencies as the reactive power consumption in the lines may increase due to heavy loading.

3.2.4 Power Flow Control of Lines in Meshed Networks.

In a meshed network the power flow may vary due to changes in generation and load patterns. The difference between phase angles in the terminal nodes of a line may change direction and may be small or vanish occasionally.

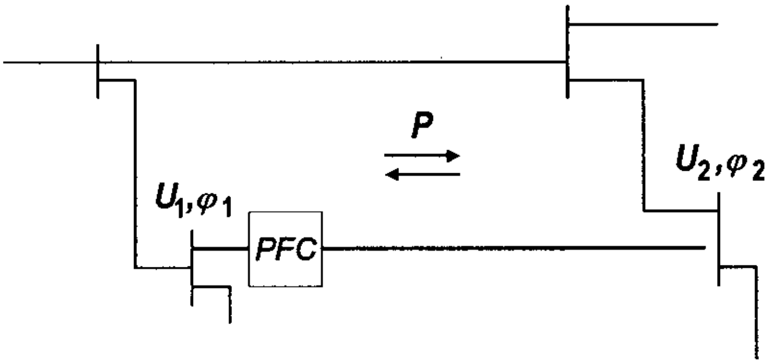


Figure 3.7: Power Flow Control in a meshed network.

The power flow can then only be controlled by a device that can provide an inserted voltage independent of the phase angles between the line terminals, i.e. PST, IPC, GTO-CSC or UPFC is required. These devices always are capable of controlling the power flow on the line where they are installed irrespective of the phase angle difference between the line terminals.

3.3 Basic Operating Principles and Basic Models of FACTS Devices

In order to understand basic theoretical principle of each FACTS device, basic relations will be presented. At this stage, devices are considered to be ideal (no active and reactive losses).

3.3.1 Controlled Series Compensation (CSC)

A general CSC concept is shown in Fig. 3.8a. The variation of the capacitance can be achieved by switching on or off (bypassing) the parts of the serially connected capacitor banks (Thyristor Switched Series Compensation - TSSC) and/or by varying the thyristor controlled reactor (TCR) reactance which is connected parallel to the capacitor (thyristor controlled series compensation - TCSC). The TCR reactance is determined by the TCR thyristor valve switching angle. The interdependence between the TCSC reactance and the TCR thyristor valve switching angle is shown in Fig. 3.8b.

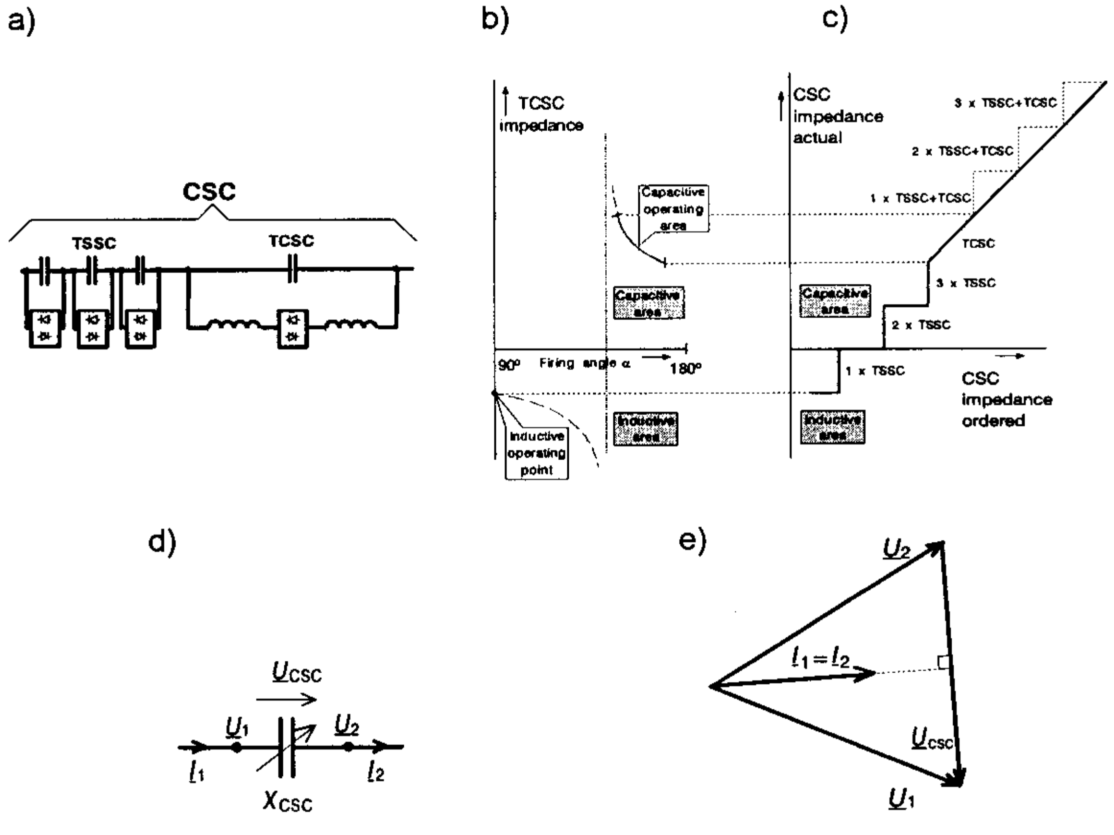


Figure 3.8 a) CSC concept
b) TCSC reactance vs. TCR firing angle
c) CSC actual impedance vs. CSC required impedance
d) The basic scheme of the CSC model
e) CSC vector diagram

For practical reasons only a part of impedance characteristic is used in normal operation (capacitive operating area and inductive operating point). However, in the future it can be expected that the inductive range will also be utilised. With suitable CSC control, using both types of equipment (TSSC and TCSC), in the large part of the CSC operating area continuous control is possible (Fig. 3.8c). However the presented example can be only stepwise controlled in the inductive and in the low impedance capacitive area.

The TSSC current is equal to the line current, the currents through the capacitance and the of the TCSC can be however considerably higher (theoretically infinite at the point of resonance).

In a simplified study CSC can be considered a controllable reactance (normally capacitance), which is connected serially to the transmission line (Fig. 3.8d). The vector diagram is presented in Fig. 3.8e. The basic principles of the CSC are in detail presented in [3,4].

Basic mathematical relations according to Fig. 3.8d are:

$$\underline{I}_1 = \underline{I}_2 = \underline{I}; \quad \underline{U}_{CSC} = -jX_{CSC}\underline{I} \tag{3.1}$$

Where X_{CSC} is the reactance of the CSC and is the controllable parameter.

3.3.2 Controlled Series Compensation with GTO Converter (GTO-CSC)

While in a CSC the reactive power is produced or consumed in energy storage elements (capacitors and reactors) another approach is possible using power electronics elements with turn-off capability (GTO's for instance). By proper power electronics elements repetitive switching, the phases of the system are connected and/or disconnected causing reactive power flowing among them.

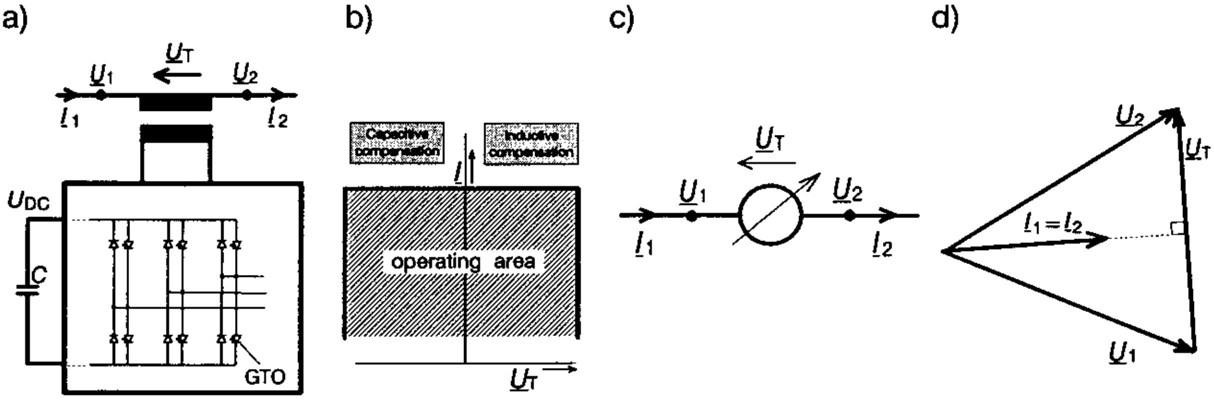


Figure 3.9 a) GTO-CSC concept
b) GTO-CSC operating characteristic
c) Basic scheme of the GTO-CSC model
e) GTO-CSC vector diagram

A possible GTO-CSC schematic diagram and its operating characteristic is shown in Fig. 3.9. The main difference to the CSC is that the injected GTO-CSC voltage $\underline{U}_T$ does not depend on line current $\underline{I}$ therefore a GTO-CSC can be modelled as a controllable reactive voltage source (Fig. 3.9c), with line current $\underline{I}$ and GTO-CSC injected voltage $\underline{U}_T$ being perpendicular to each other. The vector diagram is the same as in the CSC case (Fig. 3.9d).

Basic mathematical relations according to Fig. 3.9c are:

$$\underline{I}_1 = \underline{I}_2 = \underline{I}; \qquad \underline{U}_T = \pm j \frac{\underline{I}}{|\underline{I}|} U_T \tag{3.2}$$

The controllable GTO-CSC parameter is U_T. The representation of the controller in a stability program is given in the section 3.5.2.

3.3.3 Static Var Compensator (SVC)

Basically an SVC consists of a combination of fixed capacitors or reactors, thyristor switched capacitors and thyristor controlled reactors connected in parallel with the electrical system [5]. The basic scheme and SVC operating characteristic are shown in Fig. 3.10a and 3.10b. The maximal SVC reactive currents are linearly dependent on SVC terminal voltage (Fig 3.10b). Thus an SVC acts as a controllable parallel susceptance (capacitive or inductive) and can be represented as a controllable reactive susceptance connected in parallel to the network (Fig. 3.10c). The reactive power produced or consumed by an SVC is generated in passive reactive power components.

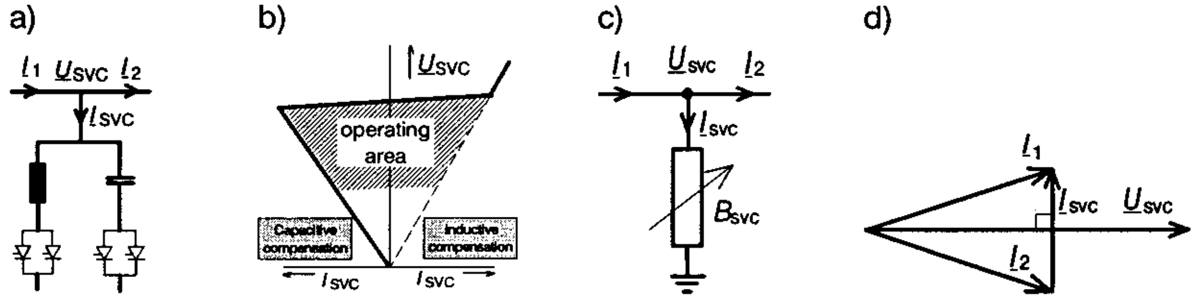


Figure 3.10
a) SVC concept
b) SVC steady operating characteristic
c) Basic scheme of the SVC model
e) SVC vector diagram

Basic mathematical relations are:

$$\underline{I}_{SVC} = \underline{U}_{SVC}\, j\, B_{SVC} \tag{3.3}$$

An SVC operates in capacitive mode if $B_{SVC} > 0$ and in inductive mode when $B_{SVC} < 0$. The susceptance B_{SVC} can be in a certain range (the SVC rating) continuously controlled. If SVC operating point reaches its capacitive or inductive limit, it acts as a parallel capacitor or reactor, respectively.

3.3.4 Static Var Generator (SVG)

As an CSC can be improved to a GTO-CSC by using a GTO converter, so can an SVC be improved to an SVG (STATCOM). Like an SVC, a SVG also represents controllable parallel compensation. It basically consists of a GTO converter and a DC circuit (Fig. 3.11a). In the simplest form the latter consists of the capacitor [6]. The reactive power generation or absorption is as in the GTO-CSC case performed by system itself, in balanced conditions reactive elements being necessary for energy storage between short periods between semiconductor switching. From the SVG operating characteristic (Fig. 3.11b) it is evident that, the system can be supplied by the constant reactive current $\underline{I}_{SVG}$ in the almost entire range independent of the terminal voltage $\underline{U}_{SVG}$. Therefore an SVG can in the studies be visualised as a parallel reactive current source connected to the system (Fig. 3.11c). The controllable SVG parameter is its reactive current $\underline{I}_{SVG}$.

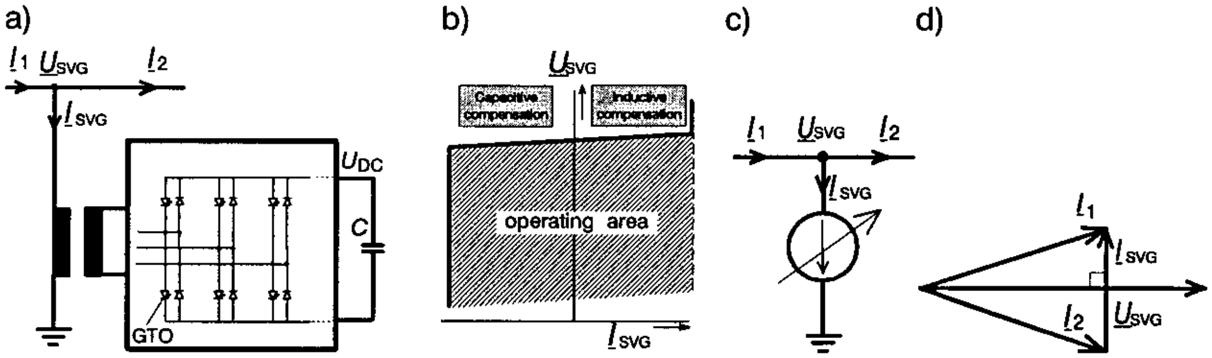


Figure 3.11
a) SVG concept
b) SVG operating characteristic
c) Basic scheme of the SVG model
e) SVG vector diagram

Basic mathematical relations are:

$$\mathrm{Arg}(\underline{I}_{SVG}) = \mathrm{Arg}(\underline{U}_{SVG}) \pm 90^\circ \qquad (3.4)$$

In the capacitive SVG operating mode the vector $\underline{I}_{SVG}$ is leading the voltage, whilst in the inductive SVG operating mode it lags the voltage vector $\underline{U}_{SVG}$ by 90°.

3.3.5 Phase Shifting Transformer (PST)

PST is a transformer with a complex turn ratio. The phase angle difference between the PST terminal voltages is achieved by serially connecting a boosting transformer into the transmission line (Fig. 3.12a). The power (active and reactive), which is injected into the transmission line by this boosting transformer (by injected voltage $\underline{U}_T$) must be taken from the network by the shunt transformer (PST parallel branch) and led to the boosting transformer. Neglecting losses, the PST does not produce nor consume active and/or reactive power. The PST can be considered a real power "accelerator". Real power is "pulled" by the PST parallel branch from the system and "pushed" by the PST series branch back into the system or vice versa. Thus a "loop flow" is generated. Different PST designs are possible. In this report the design with two transformers (cf. Fig. 3.12a) is considered.

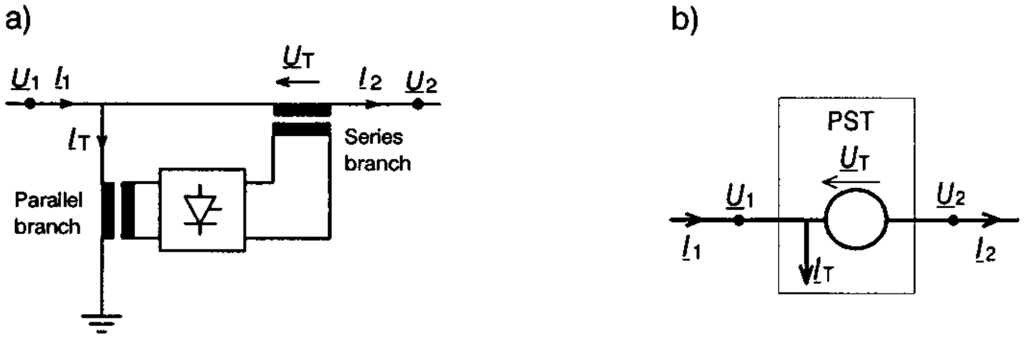


Figure 3.12 a) Basic scheme of the PST
b) Basic PST model

From the electrical point of view two PST types will be studied. The first one is a PST, with equal magnitude input and output voltages but with a phase shift between these voltages. This is the so-called "Phase Angle Regulator" (PAR). The second PST, is the so-called "Quadrature Boosting Transformer" (QBT). The phasor of the injected voltage of the QBT series branch is shifted by a constant angle with respect to the input voltage vector. In following analysis it is assumed, that the PSTs are continuously controllable by static on-load tap changers [7].

The model has been derived from the physical behaviour of the device. It consists of voltage source $\underline{U}_T$, which represents the PST series branch and current source $\underline{I}_T$ representing the PST parallel branch. Power injected into the system by voltage source $\underline{U}_T$ is taken from the system by current $\underline{I}_T$, so the PST power is balanced. The representation of PST in a stability program is given in section 3.5.2.

3.3.5.1 Phase Angle Regulator (PAR)

The controllable parameter of the PAR is the voltage shift angle α. The voltage and current magnitudes of both terminals are equal. In Fig. 3.13 the PAR steady state operating characteristic and a vector diagram are shown.

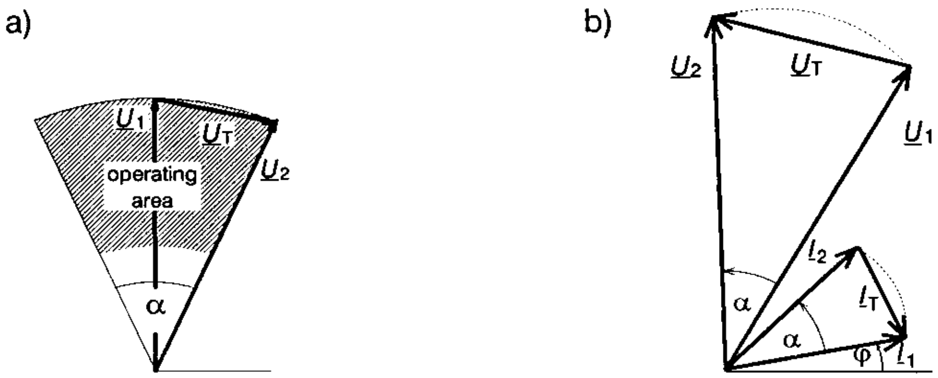


Figure 3.13 a) PAR operating characteristic
b) PAR vector diagram

Basic mathematical relations are:

$$\underline{U}_2 = \underline{U}_1 . e^{j\alpha} \tag{3.5}$$

$$\underline{I}_2 = \underline{I}_1 . e^{j(\varphi+\alpha)} \tag{3.6}$$

3.3.5.2 Quadrature Boosting Transformer (QBT)

The controllable Parameter of the QBT is the magnitude of the injected voltage $\underline{U}_T$ (Fig. 3.14). Angle β is constant. Various types of QBT enable various β angles. In the UK and Central Europe the commonly used QBT is the one in which the voltage $\underline{U}_T$ is perpendicular to the input terminal voltage $\underline{U}_1$ (β=90°), therefore this case will be discussed. The operating characteristic and the vector diagram are shown in Fig 3.14.

Basic mathematical relations are:

$$\underline{U}_2 = \underline{U}_1 . (1 + j \frac{U_T}{U_1}) = \underline{U}_1 . K . e^{j\alpha} \tag{3.7}$$

$$\underline{I}_2 = \frac{\underline{I}_1}{K^2} . \left(1 + j \frac{U_T}{U_1}\right) = \frac{\underline{I}_1}{K} . e^{j\alpha} \tag{3.8}$$

where:

$$K = \sqrt{1 + \left(\frac{U_T}{U_1}\right)^2} ; \quad \alpha = \arctan\left(\frac{U_T}{U_1}\right) \tag{3.9}$$

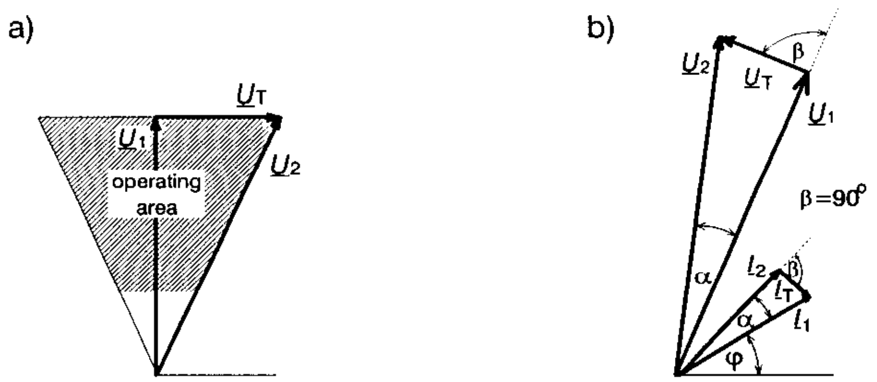


Figure 3.14 a) QBT static operating characteristic
b) QBT vector diagram

3.3.6 Interphase Power Controller (IPC)

The Interphase Power Controller is a series-connected controller, where the essential components in each phase are an inductor and a capacitor subjected to individually phase- shifted voltages. The IPC can take many forms, depending on the application requirements and on the method used to implement the internal phase-shifts. The single-phase equivalent circuit (which also serves for modelling in load flow programs), is given in Fig. 3.15a.

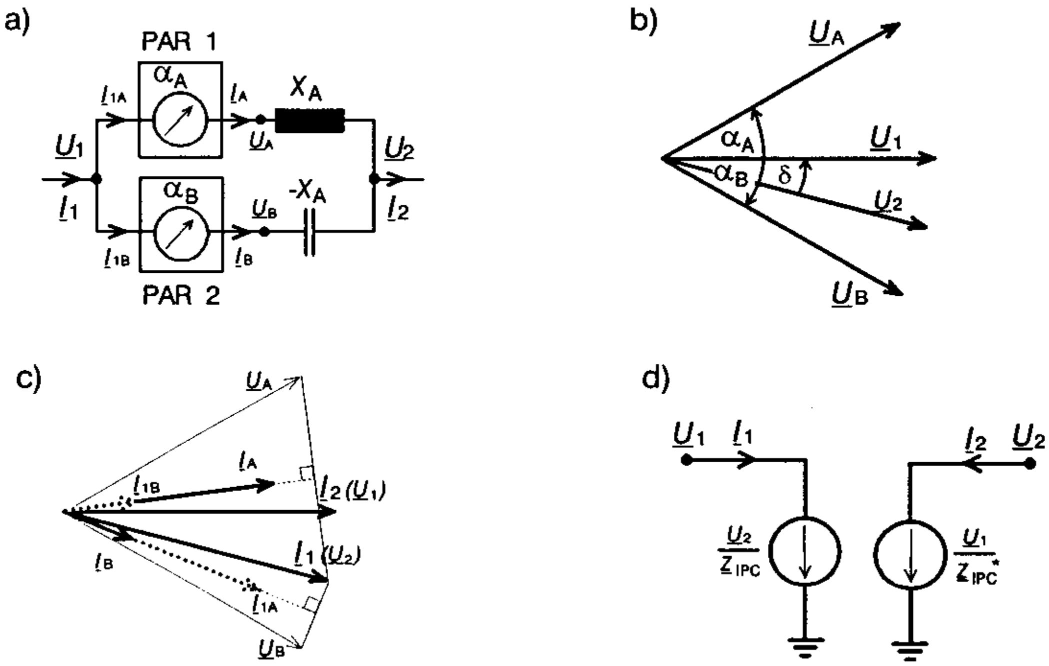


Figure 3.15 a) IPC equivalent circuit
b) IPC voltage vector diagram ($\alpha_A = -\alpha_B$)
c) IPC current vector diagram ($\alpha_A = -\alpha_B$)
d) IPC equivalent model

In the particular case where the reactor and the capacitor form a conjugate pair, each terminal of the IPC behaves as a voltage-dependent current source. The voltage and current vector diagrams and the equivalent model are presented in Fig. 3.15b, 3.15c and 3.15d respectively. Further information is available in references [8], [9] and [10].

The basic mathematical relations are:

$$\underline{I}_1 = \frac{\underline{U}_2}{\underline{Z}_{\mathrm{IPC}}}; \quad \underline{I}_2 = \frac{\underline{U}_1}{\underline{Z}_{\mathrm{IPC}}^{*}} \tag{3.10}$$

where:

$$\underline{Z}_{\mathrm{IPC}} = X_{\mathrm{IPC}}\, e^{j\alpha_{\mathrm{IPC}}}, \qquad X_{\mathrm{IPC}} = \frac{X_{\mathrm{A}}}{2\sin\left(\frac{\alpha_{\mathrm{A}} - \alpha_{\mathrm{B}}}{2}\right)}; \qquad \alpha_{\mathrm{IPC}} = \frac{\alpha_{\mathrm{A}} + \alpha_{\mathrm{B}}}{2} \tag{3.11}$$

3.3.7 Unified Power Flow Controller (UPFC)

The basic structure of the UPFC concept is shown in Fig. 3.16a. It consists of shunt (exciting) and series (boosting) transformer. Both are connected by two GTO converters and a DC circuit represented by the capacitor. The basic difference between a UPFC and a PST is, that the UPFC reactive power injected into the line by the series branch does not need to be transmitted from the parallel branch. It is generated in series branch as in case of GTO-CSC. The real power injected into the system by the series branch must, of course, be taken from the system by the parallel branch (current $\underline{I}_{\mathrm{T}}$) and transmitted to the series branch over the DC circuit. Additionally, the reactive current of the parallel branch $\underline{I}_{\mathrm{q}}$ can be controlled in the same manner as it is done in an SVG. This current is represented by a current source.

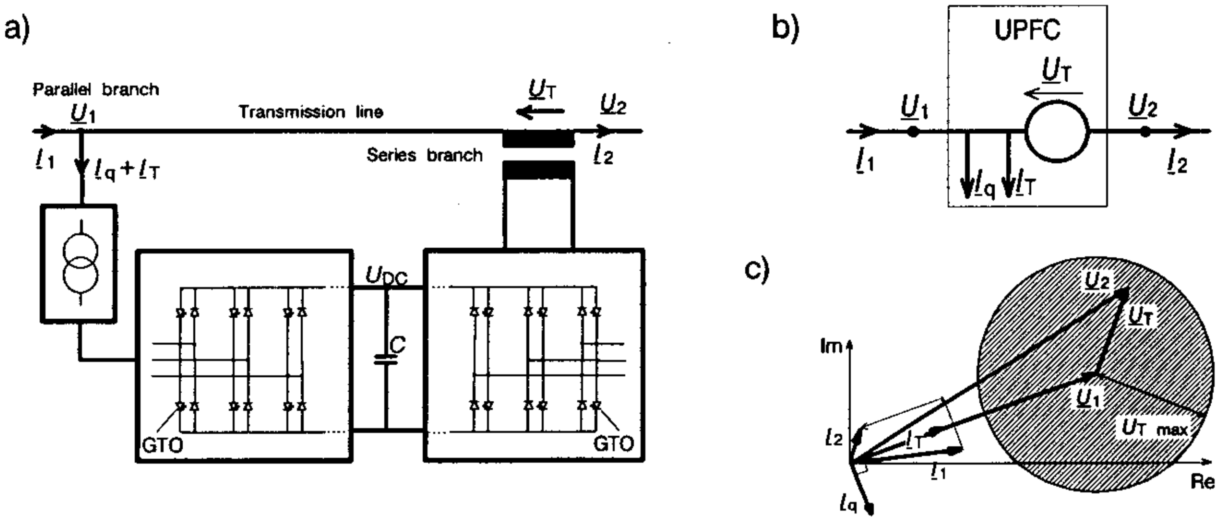


Figure 3.16 a) Basic scheme of the UPFC
b) Scheme of the UPFC model
c) Vector diagram

The phasor $\underline{U}_T$ can be at any phase with regard to $\underline{U}_1$ and can have any magnitude ranging from 0 to U_{Tmax} corresponding to the UPFC dimensions. The operating area becomes the area limited by a circle defined by U_{Tmax}. More details about operating principles are described in [11]. The controlled UPFC parameters are phase and magnitude of the voltage $\underline{U}_T$ and the magnitude of the reactive current $\underline{I}_q$. The UPFC representation for the use in a stability program is described in section 3.5.2.

The UPFC model, shown in Fig. 3.16b, consists of voltage source $\underline{U}_T$ and two current sources $\underline{I}_T$ and $\underline{I}_q$. Voltage source $\underline{U}_T$ represents the UPFC series branch voltage injection. Real power which is in this way injected into the system is taken from the system by current source $\underline{I}_T$. The controllable reactive current of the parallel branch is represented by the current source $\underline{I}_q$.

According to vector diagram a UPFC resembles a PST. But a PST does not produce nor consume reactive power (neglecting losses) in contrast to a UPFC which includes two independent reactive power sources (reactive power injected into the line via series branch and the reactive current of the parallel branch). In this way a UPFC combines characteristics of GTO-CSC, SVG and PST. The vector diagram is shown in Fig 3.16c.

The basic mathematical relations are:

$$\underline{U}_2 = \underline{U}_1 + \underline{U}_T \tag{3.12}$$

$$\mathrm{Arg}(\underline{I}_q) = \mathrm{Arg}(\underline{U}_1) \pm 90^\circ \tag{3.13}$$

$$\mathrm{Arg}(\underline{I}_T) = \mathrm{Arg}(\underline{U}_1) \tag{3.14}$$

$$I_T = \frac{\mathrm{Re}\left[\underline{U}_T \underline{I}_2^*\right]}{U_1} \tag{3.15}$$

3.4 Power Flow Control in Transmission Systems

In order to understand the basic physical phenomena occurring when FACTS controllers are inserted into an electrical network, the basic relations are shown for a simple transmission application. The following FACTS controllers are considered in sequence: CSC, GTO-CSC, SVC, SVG, PAR, QBT, IPC and UPFC. For each case the system model consists of the model of the FACTS device (developed in sec. 3.3) and of system impedance (lumped inductive reactance).

The model of a transmission system without FACTS, the phasor diagram and the transmission characteristic are shown in Fig. 3.17. For each FACTS application, basic mathematical relations are expressed for the active and reactive power at both ends of the transmission system.

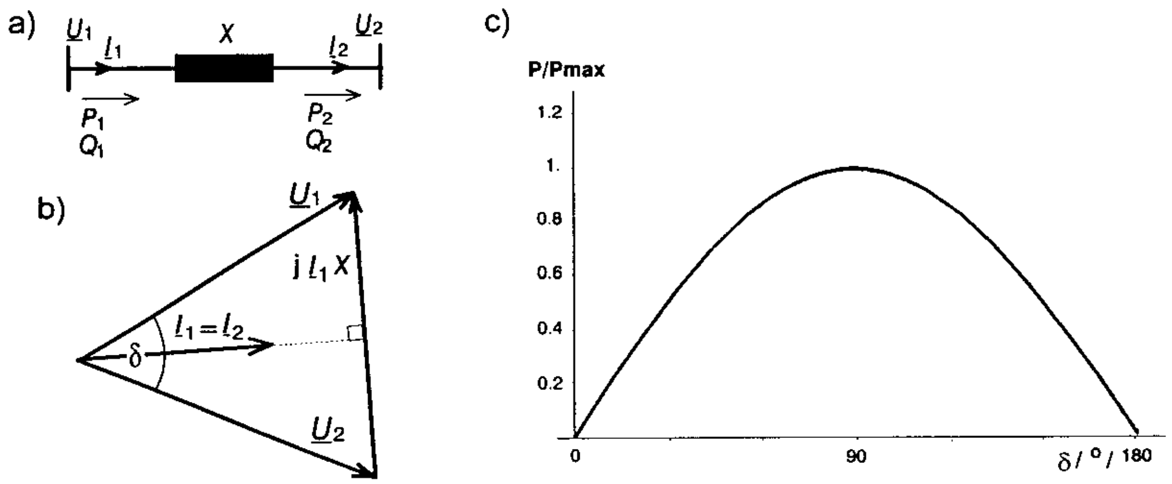


Figure 3.17

a) Transmission line model
b) Vector diagram
c) Transmission characteristic

Basic mathematical relations for the transmission system without FACTS are:

$$\underline{I}_1 = \underline{I}_2 \tag{3.16}$$

$$P_1 = P_2 = \frac{U_1 U_2}{X}\sin(\delta) = P_{MAX}\sin(\delta) \tag{3.17}$$

$$Q_1 = \frac{U_1}{X}(U_1 - U_2\cos(\delta)) \tag{3.18}$$

$$Q_2 = \frac{U_2}{X}(U_1\cos(\delta) - U_2) \tag{3.19}$$

The interdependence between the real power flow and transmission angle δ (transmission characteristic) is presented in Fig 3.17c.

3.4.1 Controlled Series Compensation (CSC)

The model of the network with the connected CSC and the corresponding vector diagram are shown in Fig. 3.18. Because the voltage drop on the capacitor is opposite to the voltage drop on the line inductance, the transmission system impedance equals the difference between X and the CSC controllable parameter X_C.

Basic mathematical relations are:

$$\underline{I}_1 = \underline{I}_2 \tag{3.20}$$

$$P_1 = P_2 = \frac{U_1 U_2}{X - X_C}\sin(\delta) \tag{3.21}$$

$$Q_1 = \frac{U_1}{X - X_C}(U_1 - U_2\cos(\delta)) \tag{3.22}$$

$$Q_2 = \frac{U_2}{X - X_C}(U_1\cos(\delta) - U_2) \tag{3.23}$$

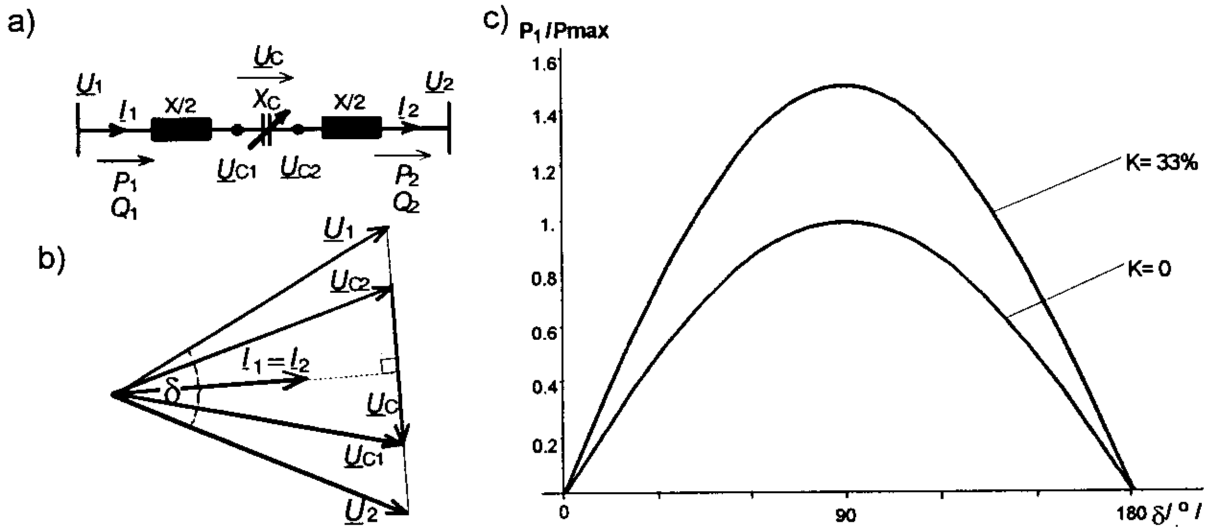


Figure 3.18 a) CSC in the middle of the transmission line
b) Vector diagram - CSC in the middle of the transmission line
c) Transmission characteristics

The dependency between the real power flow and the transmission angle δ (transmission characteristics) for compensation degree K=0 (X_C=0) and for compensation degree K=33% (X_C=X_{Cmax}=X/3) is presented in Fig. 3.18c. If X_C can be controlled between 0 and X_{Cmax}, the area between the plotted transmission characteristics is the possible operating area.

3.4.2 Controlled Series Compensation with GTO Converter (GTO-CSC)

Basically the GTO-CSC effect on the transmission characteristic is similar to the effect of the CSC. However the GTO-CSC controllable parameter is the voltage injected into the line being (for the major part of the operating area) independent of the magnitude of the line current while in the CSC case the voltage drop on the device is caused by the line current. Therefore, in the cases where transmission angles are small (and thus also the line currents), the CSC impact on transmitted power is quite limited, compared to the GTO-CSC impact, because the voltage drop on the device is the quantity which directly controls the line power flow. The GTO-CSC model included into the studied transmission system model, the GTO-CSC vector diagram and the transmission characteristics are shown in Fig. 3.19.

Basic mathematical relations are:

$$\underline{I}_1 = \underline{I}_2 \tag{3.24}$$

$$P_1 = P_2 = \frac{U_1 U_2 \sin(\delta)}{X}\left(1 - \frac{U_T}{\sqrt{U_1^2 + U_2^2 - 2U_1 U_2 \cos(\delta)}}\right) \tag{3.25}$$

$$Q_1 = \frac{U_1(U_1 - U_2 \cos(\delta))}{X}\left(1 - \frac{U_T}{\sqrt{U_1^2 + U_2^2 - 2U_1 U_2 \cos(\delta)}}\right) \tag{3.26}$$

$$Q_1 = \frac{U_2(U_2 - U_1 \cos(\delta))}{X}\left(1 - \frac{U_T}{\sqrt{U_1^2 + U_2^2 - 2U_1 U_2 \cos(\delta)}}\right) \tag{3.27}$$

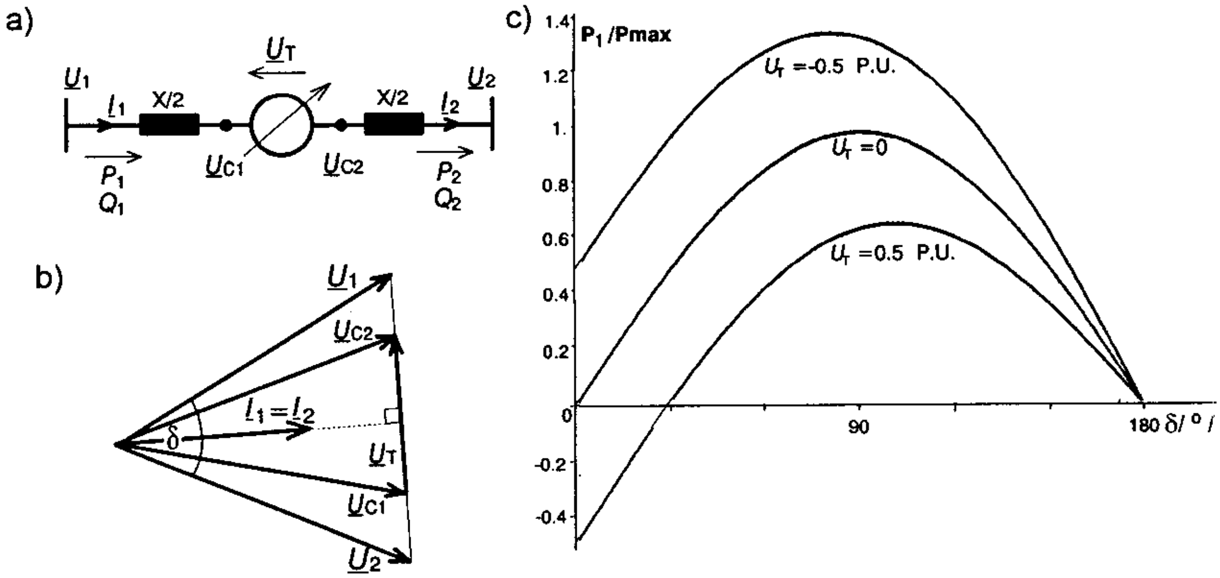


Figure 3.19
- a) GTO-CSC in the middle of the transmission line
- b) Vector diagram with GTO-CSC in the middle of the transmission line
- c) Transmission characteristics

3.4.3 Static Var Compensator (SVC)

There are two possible explanations of the influence of a SVC on the real power flow in the system. The first one the so-called constant voltage principle, the second one, however, is the representation of the SVC by a parallel connected susceptance B_{SVC} corresponding to the instantaneously operating point of the SVC (Fig. 3.20a).

If the SVC is large enough to control the terminal voltage to a constant value, the transmission line is split into two independent parts. In this case (Fig. 3.20a) the line length is electrically reduced to 1/2.

If the SVC is represented by a parallel connected susceptance the system impedance scheme can be transformed by "Y - D" transformation (Fig. 3.20c). The effect on the transmission line is in this simple case the same as though the series compensation with the compensation degree $K = (X.B_{SVC})/4$ were used. Taking into account equations (3.21) and (3.28) and assuming transmission angle $\delta=30°$ it is obvious that the rating of a corresponding CSC would give a SVC rating of more than one order of magnitude higher.

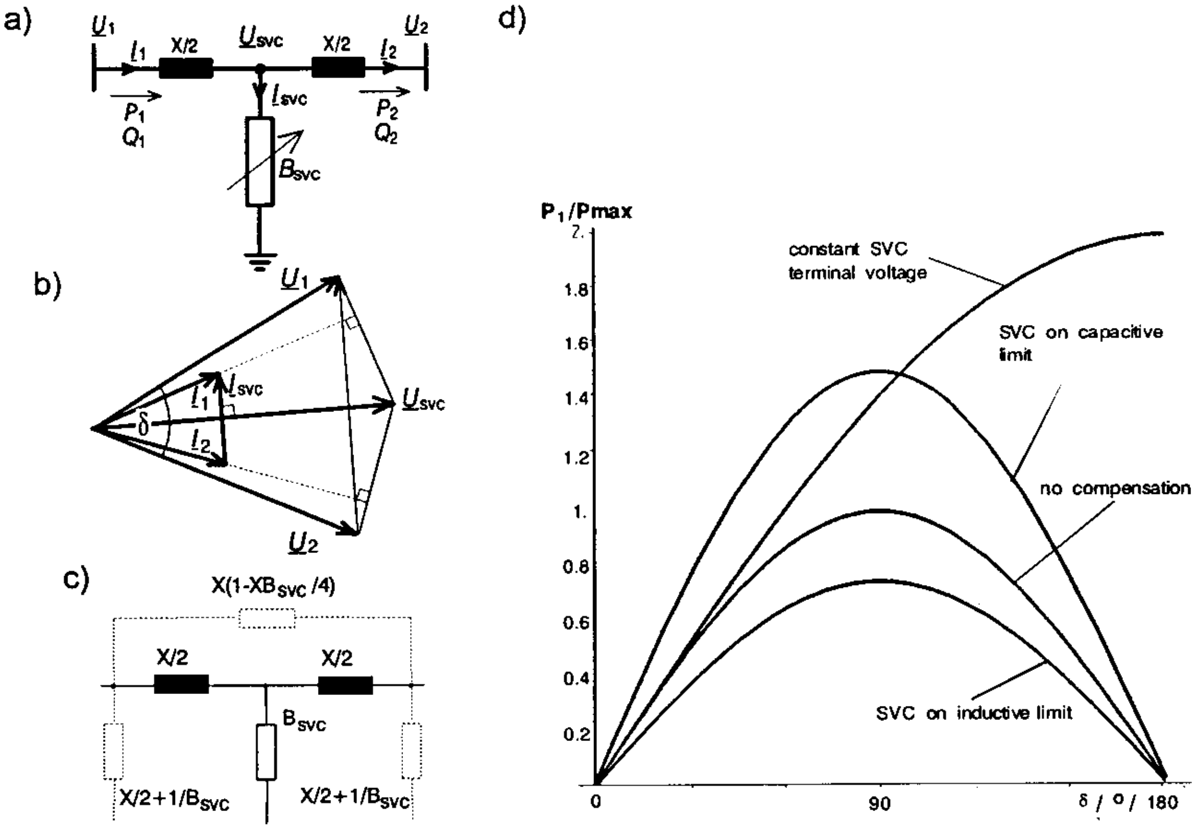


Figure 3.20 a) SVC in the middle of the transmission line
b) SVC vector diagram
c) Impedance scheme of the network
d) Transmission characteristic

The P(δ) characteristics reduced to the maximum transmittable power Pmax for different SVC operating points are shown in Fig. 3.20d. For economic reasons, the SVC can not be rated as to provide constant voltage over the whole range of transmission angles δ i.e. 180° (it would electrically shorten the line by half; if $U_1=U_2=U_{SVC}$ the necessary rated SVC power would be 4 Pmax). Above a certain angle δ (crossing of "constant SVC terminal voltage" and "SVC on capacitive limit" curves in Fig. 3.20d) the principle of constant voltage can not be applied any more and SVC acts as a parallel connected capacitor (SVC capacitive limit).

The active and reactive power at both ends of the transmission line are:

$$P_1 = P_2 = \frac{U_1 U_2}{X\left(1 - \frac{X B_{SVC}}{4}\right)} \sin(\delta) \tag{3.28}$$

$$Q_1 = \frac{U_1}{X\left(1 - \frac{X B_{SVC}}{4}\right)} \left(U_1 - U_2 \cos(\delta)\right) \tag{3.29}$$

$$Q_2 = \frac{U_2}{X\left(1 - \frac{X B_{SVC}}{4}\right)} \left(U_1 \cos(\delta) - U_2\right) \tag{3.30}$$

If B_{SVC} can be controlled between maximum value (capacitive limit) and minimum value (inductive limit), the area between the transmission characteristics "SVC on capacitive limit" and "SVC on inductive limit" is the operating area (Fig. 3.20d). The curve of the constant voltage U_{SVC} is also presented.

3.4.4 Static Var Generator (SVG)

When a SVG is connected to the transmission line (the model of the network with an SVG and the vector diagram are shown in Fig. 21a and 21b respectively), circumstances are basically similar to those in the case of an SVC. The transmission characteristics are shown in Fig 21c. In order to compare the effect of SVCs and SVGs effect on transmission characteristics, SVC characteristics are also plotted. The SVG current has been selected so as to equal the SVC current at 1 P. U. terminal voltage. The SVG capacitive limit characteristic is below the SVC characteristic until terminal voltage drops below 1 P.U. If voltages U_1 and U_2 drop, the area in which SVG characteristic is over the SVC characteristic expands.

If I_{SVG} can be controlled between its maximal and minimal values, the area between the transmission characteristics "SVG on capacitive limit" and "SVG on inductive limit" is the operating area.

Basic mathematical relations are:

$$P_1 = P_2 = \frac{U_1U_2}{X}\left(1+\frac{I_{SVG}X}{2\sqrt{U_1^2+U_2^2+2U_1U_2\cos(\delta)}}\right)\sin(\delta) \qquad (3.31)$$

$$Q_1 = \frac{U_1^2}{X}-\frac{U_1U_2}{X}\cos(\delta)+\frac{I_{SVG}}{2} \qquad (3.32)$$

$$Q_2 = \frac{U_1U_2}{X}\cos(\delta)-\frac{U_2^2}{X}-\frac{I_{SVG}}{2} \qquad (3.33)$$

If $U_1 = U_2 = U$

$$P_1 = P_2 = \frac{U^2}{X}\sin(\delta)+\frac{UI_{SVG}}{2}\sin(\delta/2) \qquad (3.34)$$

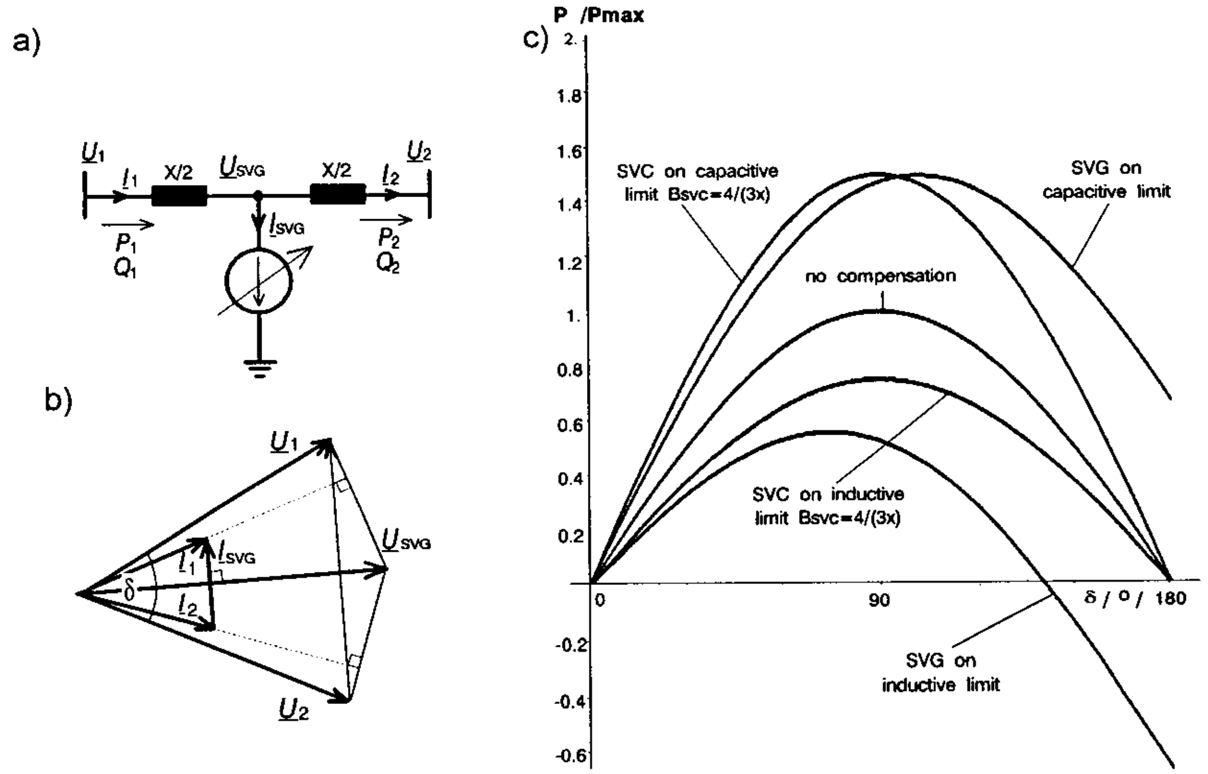


Figure 3.21 a) SVG in the middle of the transmission line
b) Vector diagram
c) Transmission characteristic

3.4.5 Phase Angle Regulator (PAR)

The model of the network with a PAR and the vector diagram are shown in Fig. 3.22a and 3.22b respectively. In this case the PAR is located at the transmission line terminal. The location (neglecting PAR losses) has no impact on transmission line power flows.

Basic mathematical relations are:

$$P_1 = P_2 = \frac{U_1 U_2}{X}\sin(\delta + \alpha) \tag{3.35}$$

$$Q_1 = \frac{U_1}{X}\left(U_1 - U_2 \cos(\delta + \alpha)\right) \tag{3.36}$$

$$Q_1 = \frac{U_2}{X}\left(U_1 \cos(\delta + \alpha) - U_2\right) \tag{3.37}$$

The transmission characteristics are shown in Fig 3.22c. If the PAR can be continuously controlled between its maximum and minimum phase shifts α_{max} and α_{min}, the area between the transmission characteristics $\alpha = \alpha_{max}$ and $\alpha = \alpha_{min}$ is the operating area.

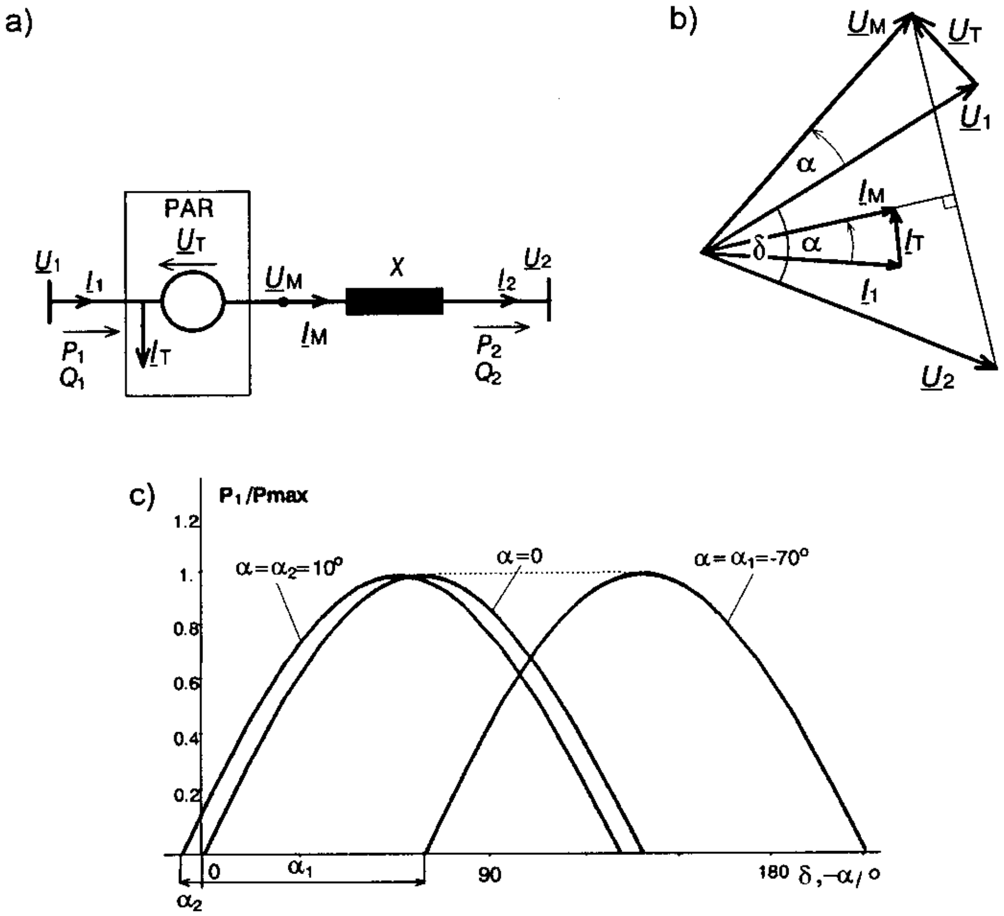


Figure 3.22 a) PAR at the transmission line terminal
b) Vector diagram
c) Transmission characteristics

3.4.6 Quadrature Boosting Transformer (QBT)

Like the PAR, the QBT is in this presentation also located at the transmission line terminal. The model of the network with a QBT and the vector diagram are presented in Fig. 3.23a and 3.23b respectively. In contrast to a PAR in the case of a QBT its location in the transmission line has a marked impact on the transmission characteristics (this also assumes that losses are neglected) [12], [24]. The reason for this is that not only the phase angle but also the magnitude of the outgoing terminal QBT voltage changes with phase shift angle.

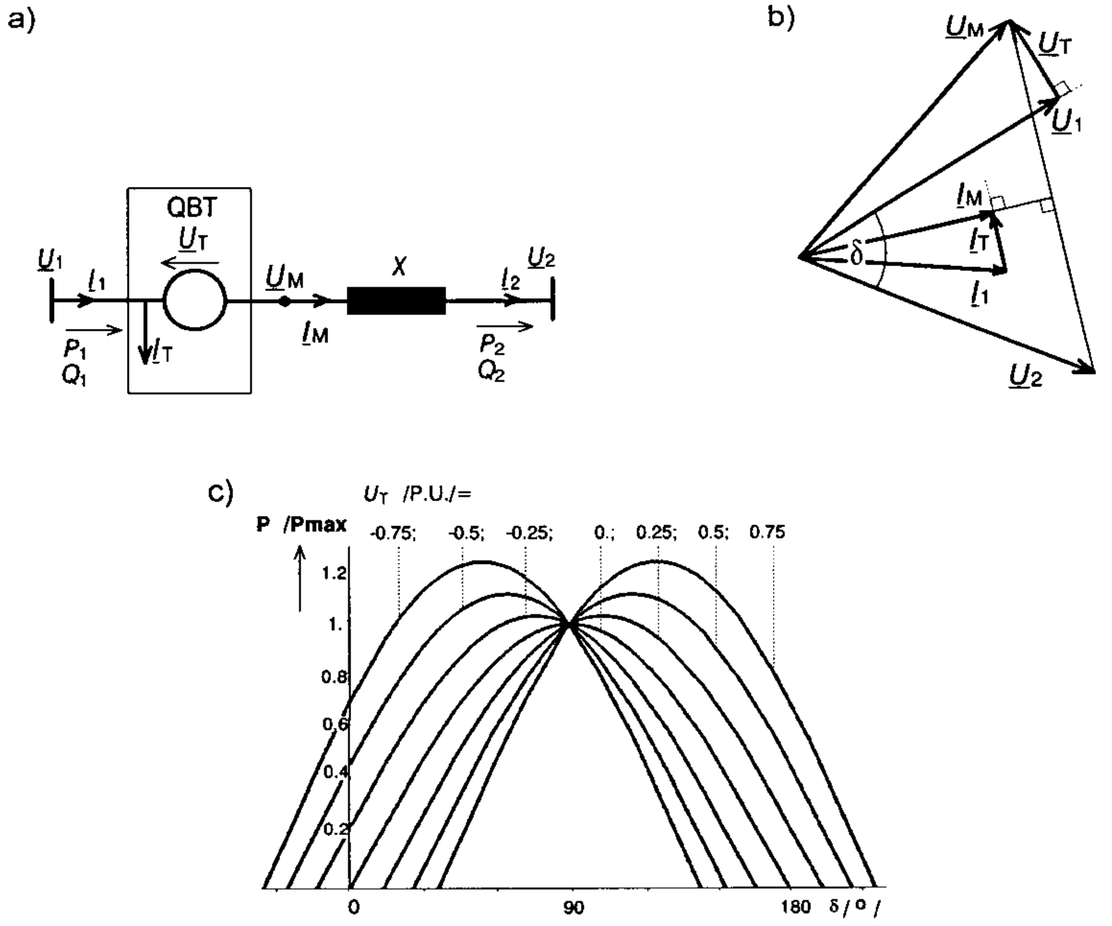


Figure 3.23

a) QBT at the transmission line terminal
b) Vector diagram
c) Transmission characteristics

Basic mathematical relations are:

$$P_1 = P_2 = \frac{U_2}{X}\left(U_T \cos(\delta) + U_1 \sin(\delta)\right) \tag{3.38}$$

$$Q_1 = \frac{1}{X}\left(U_1^2 + U_T^2 - U_2\left(U_1 \cos(\delta) - U_T \sin(\delta)\right)\right) \tag{3.39}$$

$$Q_2 = \frac{U_2}{X}\left(U_1 \cos(\delta) - U_T \sin(\delta) - U_2\right) \tag{3.40}$$

The transmission characteristics for various QBT controllable parameter (U_T) values are shown in Fig 3.23c. If the QBT can be continuously controlled between its maximum and minimum injected voltages (U_T ranging from -0.75 to +0.75 P.U.), the area between the transmission characteristics $U_T=U_{Tmin}$ (-0.75 P.U. cf. Fig. 3.23) and $U_T=U_{Tmax}$ (+0.75 P.U. cf. Fig. 3.23) is the operating area.

3.4.7 Interphase Power Controller (IPC)

The basic IPC presented in section 3.3.6 has three controllable parameters: the two internal phase-shift angles (α_A and α_B) and the magnitude of the reactance X_A. In order to demonstrate the impact of the IPC on power flow, an IPC is connected between a stiff voltage source and an external impedance, as shown in Fig 3.24a. The vector diagram and transmission characteristic are presented in Fig. 3.24b and 3.24c. From the mathematical relations, it is evident that when the transmission characteristic is properly located with respect to the transmission angle of the network, the IPC maintains the transmitted real power almost constant (for example, if $\alpha_{IPC}=0$ and the transmission angle ranges from -20° to 20°, real power changes by no more than 6%) without any control action or delays, because the control characteristic is inherent to the IPC.

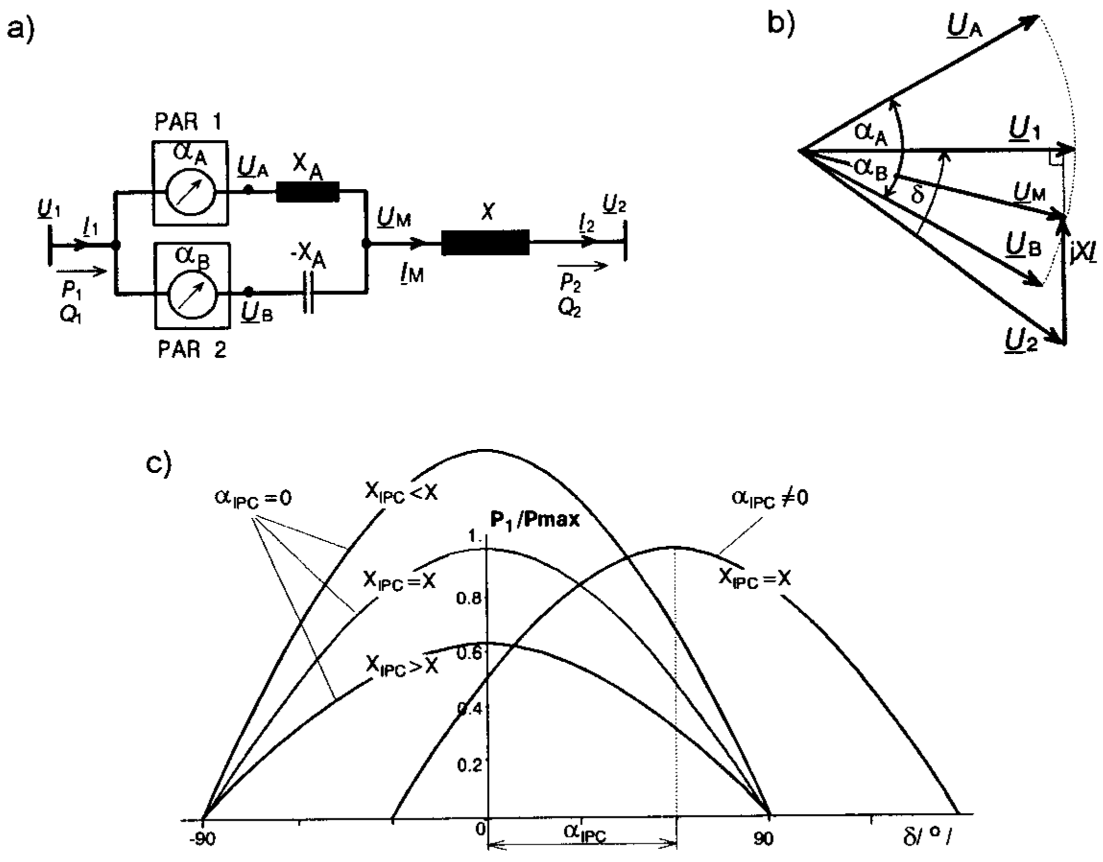


Figure 3.24 a) IPC connected to a transmission system
b) Vector diagram ($\alpha_B = -\alpha_A$)
c) Transmission characteristics

Since the IPC behaves as voltage-dependent current sources, the real power does not depend on the external reactance X and the IPC does not contribute to short circuit currents. The level of the transmitted power and the amount of reactive power generated/absorbed by each side of the IPC can be controlled, independently one from the other, by controlling the IPC parameters α_A, α_B and X_A. In practical applications, the reactances can be kept constant while one or two degrees of freedom can be provided by the phase shifts.

Basic mathematical relations (X_{IPC} and α_{IPC} are defined in (3.11).) are:

$$P_1 = P_2 = \frac{U_1 U_2}{X_{IPC}} \cos(\delta + \alpha_{IPC}) \tag{3.41}$$

$$Q_1 = \frac{U_1 U_2}{X_{IPC}} \sin(\delta + \alpha_{IPC}) - \frac{U_1^2 X}{X_{IPC}^2} \tag{3.42}$$

$$Q_2 = -\frac{U_1 U_2}{X_{IPC}} \sin(\delta + \alpha_{IPC}) \tag{3.43}$$

3.4.8 Unified Power Flow Controller (UPFC)

The UPFC has three controllable parameters, namely magnitude of the boosting transformer injected voltage U_T, phase of this voltage φ_T and the exciting transformer reactive current I_q. Because the UPFC is in this case considered to be located on the line terminal at which voltage is independent of line current (c.f. Fig. 3.25a), the parameter I_q has no impact on the transmission characteristics. The question is how to control the remaining two controllable parameters to achieve maximum effect, i.e. to achieve maximum or minimum transmittable real power, if the UPFC rating is given ($U_T <= U_{Tmax}$). It has been calculated that in this case U_T should be on its limit ($U_T = U_{Tmax}$) and φ_T should be 90° to achieve maximum and -90° to achieve minimum transmitted power ("optimal" angle φ_T). "Optimal" φ_T is in this case independent of U_T. However if the UPFC is positioned inside the transmission system the analytical expression for "optimal" UPFC parameter φ_T could not be found and had to be calculated numerically for each system operating point.

Basic mathematical relations are:

$$U_M = \sqrt{U_1^2 + U_T^2 + 2U_1 U_T \cos(\varphi_T - \delta)} \tag{3.44}$$

$$\alpha = \arctan\left(\frac{U_T \sin(\varphi_T - \delta)}{U_1 + U_T \cos(\varphi_T - \delta)}\right) \tag{3.45}$$

$$P_1 = P_2 = \frac{U_M U_2}{X} \sin(\delta + \alpha) \tag{3.46}$$

$$Q_1 = \frac{U_M}{X}\left(U_M - U_2 \cos(\delta + \alpha) + U_T \sin(\delta + \alpha) + X I_q\right) \tag{3.47}$$

$$Q_2 = \frac{U_2}{X}\left(U_M \cos(\delta + \alpha) - U_2\right) \tag{3.48}$$

If

$$\frac{\partial P_1}{\partial \varphi_T} = 0 \Rightarrow \varphi_T = \pm 90^\circ \tag{3.49}$$

then

$$U_M = \sqrt{U_1^2 + U_T^2 \pm 2U_1U_T\sin(\delta)} \tag{3.50}$$

$$\alpha = \arctan\left(\frac{U_T\cos(\delta)}{U_1 \pm U_T\sin(\delta)}\right) \tag{3.51}$$

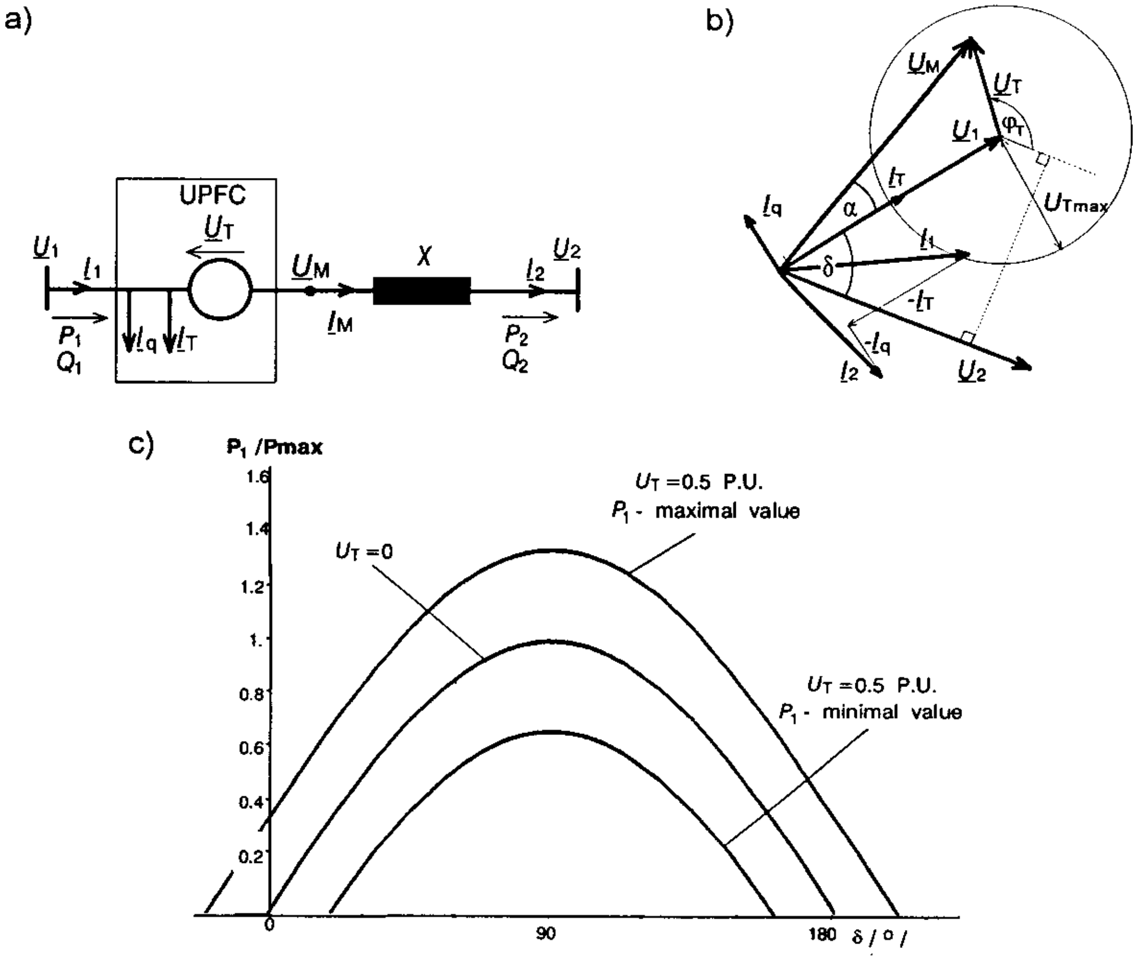


Figure 3.25

a) UPFC at the transmission line terminal
b) Vector diagram
c) Transmission characteristics

The transmission characteristics for various UPFC controllable parameters U_T (φ_T equals 90° (-90°) to guarantee the strongest UPFC impact on transmission characteristics) are shown in Fig. 3.25c (U_T=0.5 P.U. and U_T=0). The operating area is the area between the transmission characteristics "U_T=0.5, P_1-maximal value" and "U_T=0.5, P_1-minimal value".

3.5 Power Flow Control in Meshed Systems

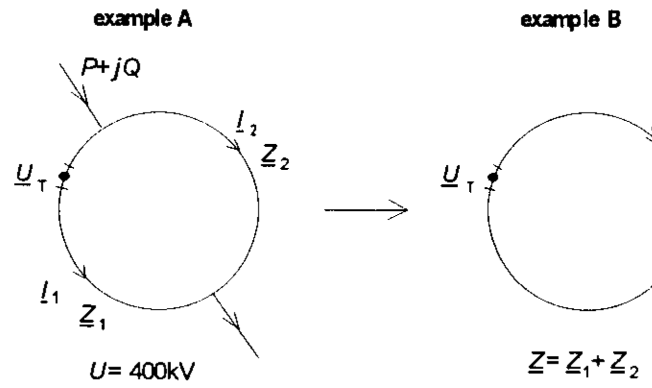
For load flow control in meshed systems the following FACTS are most suitable:

- Phase Shifting Transformer (PST) (Quadrature Boosting Transformer - QBT - was chosen)
- Controlled Series Compensation using GTO converters (CSC with GTOs) and
- Unified Power Flow Controller (UPFC).

The CSC with thyristor control, operating in the capacitive range only, can be used for load flow control in a meshed system, if it can be located at a suitable location. Shunt elements such as SVC and GTO-SVC influence load flow only marginally and are therefore used for voltage control and to support damping of oscillations.

3.5.1 Load Flow Control in a Simple System

A complex meshed system can be simplified to a system with two parallel lines forming a loop with a loop impedance $\underline{Z} = Z e^{-j\beta}$ (Fig. 3.26). This equivalent impedance can be calculated from the system configuration, loads and generation infeeds. The real part of the impedance in a loop without additional infeeds (example A in Fig. 3.26) is typically 1/10 of the inductive part. In meshed systems, however, because of the influence of loads and generators, the calculated real part of the impedance can increase, e.g. to 1/2 of the inductive part (example B in Fig. 3.26).



example A: $\underline{Z}_1 = \underline{Z}_2 = (10 + j100)\ \Omega$

example B: $\underline{Z}_1 = \underline{Z}_2 = (50 + j100)\ \Omega$

Figure 3.26: Simple system building a loop

To study the impact of FACTS equipment on load flow control in a simplified configuration, we can calculate loop power due to the FACTS equipment alone and superimpose it on the existing load flow.

Assume a voltage source which infeeds a voltage $\underline{U}_\mathrm{T} = U_\mathrm{T}\,\mathrm{e}^{-j\alpha}$ into the loop as shown in Fig. 3.26. This voltage source represents the FACTS controller. The line to ground voltage at this location should be $\underline{U} = U\,\mathrm{e}^{j0}$. The apparent power driven in the loop by the voltage source and giving the control power of the FACTS controller is:

$$\underline{S}_\mathrm{T} = 3\underline{U}\underline{I}^{*} = \frac{3UU_\mathrm{T}}{Z}\mathrm{e}^{-j(\alpha-\beta)} \tag{3.52}$$

where $\underline{I}$ is the loop current. Introducing $S_0 = 3U^2/Z$, the apparent power based on this value is:

$$\underline{s}_\mathrm{T} = \frac{\underline{S}_\mathrm{T}}{S_0} = \frac{U_\mathrm{T}}{U}\mathrm{e}^{-j(\alpha-\beta)} = p + \mathrm{j}q \tag{3.53}$$

3.5.1.1 Action of the Quadrature Boosting Transformer

Quadrature Boosting Transformer (QBT), the voltage inserted into the line is perpendicular to the line to ground voltage ($\alpha = \pm\pi/2$). The control power in this case becomes:

$$\underline{s}_\mathrm{T} = \frac{U_\mathrm{T}}{U}\mathrm{e}^{-j(\pm\frac{\pi}{2}-\beta)} \tag{3.54}$$

Fig. 3.27a shows the impact of the QBT on the power in the loop according to equation (3.54) for the two alternatives of the loop impedance. Plotted are the active and reactive power components as a function of the amplitude of U_T. The maximal amplitude of the voltage U_T has been assumed to be equal to $0.3U$. The PAR controls mainly the active power flow in the loop. The reactive power change depends strongly on angle β. In a meshed system with high β values, the change in the reactive power flow can be of a considerable amount.

3.5.1.2 Action of the GTO-CSC

The Controlled Series Compensation (CSC) using GTO converter is able to insert into the line a voltage which is perpendicular to the line current. In our simplified example, we get $\alpha = \pm\pi/2 + \arg(\underline{I}_1)$, where $\underline{I}_1$ is the sum of the loop current and the line current before the insertion of FACTS element. The control power inserted by the CSC using GTOs is then:

$$\underline{s}_\mathrm{T} = \frac{\underline{S}_\mathrm{T}}{S_0} = \frac{U_\mathrm{T}}{U}\mathrm{e}^{-j(\pm\frac{\pi}{2}+\arg(\underline{I}_1-\beta)} \tag{3.55}$$

The active and reactive part of the control power are shown in Fig. 3.27b. They depend on the line current and the angle β. In the assumed case, the ratio of the reactive power to active power at the location of the CSC was 0.5. The CSC with GTOs can insert the voltage into the loop independent of the current amplitude. However, the operation at very low line current is not possible. The equipment controls mainly active power. The influence on reactive power depending on system configuration.

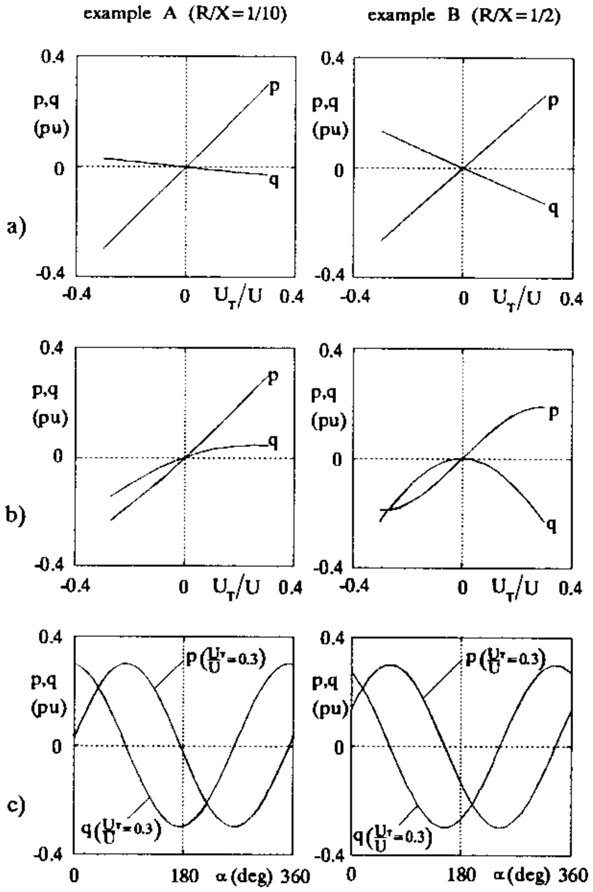


Figure 3.27: Impact of FACTS equipment on the control power in the loop
a) QBT
b) CSC with GTO
c) UPFC

3.5.1.3 Action of the Unified Power Flow Controller

The third FACTS controller studied is the Unified Power Flow Controller (UPFC). The UPFC has the ability to insert a voltage U_T of any phase angle independent of the line current into the line. In other words, the equipment can control the active or reactive power in the loop independently, however the apparent power is limited by the design of the equipment (e.g. U_T/U=0.3):

$$\underline{s}_T = \frac{U_T}{U} e^{-j(\alpha-\beta)} \tag{3.56}$$

where α can be any value between 0 and 2 π. Fig. 3.27c shows the active and reactive part of control power as a function of angle α. The angle β influences the value of the angle α at which the requested control power is achieved.

3.5.2 Load Flow Control in a Complex System

3.5.2.1 Description of FACTS Models

Calculations have been made using the stability mode of the NETOMAC program. The FACTS models used for the calculations are described in detail in [27].

The QBT and PAR can be represented by a controlled voltage source U_T and a shunt current source I_T. The QBT, PAR coordinator used in the model (Fig. 3.28) acts to fulfil the following requirements:

- if a QBT is to be represented it changes the phase of the voltage U_T simultaneously with the phase of the input terminal voltage U_A so as to keep the angle between these two voltages at 90°;
- if a PAR is modelled the phase of the voltage U_T simultaneously changes with the phase of the input terminal voltage U_A so as to keep the magnitudes of the voltages U_A and U_B equal and only angle between them is changed.
- For both i.e. QBT and PAR the apparent power S_T injected into the system by voltage source U_T is calculated and the phase and the magnitude of the current source I_T adjusted so that the same power S_T is flowing from the system. In this manner, the input and output active and reactive powers of the QBT or PAR model are balanced.

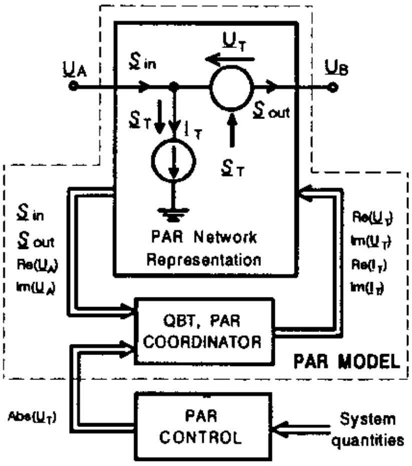


Figure 3.28: QBT and PAR model

The model of CSC using GTOs is represented by a "controlled voltage source" and includes also a coordinator (Fig. 3.29), which adjusts the phase of the injected voltage $\underline{U}_T$ so as to be perpendicular to the line current.

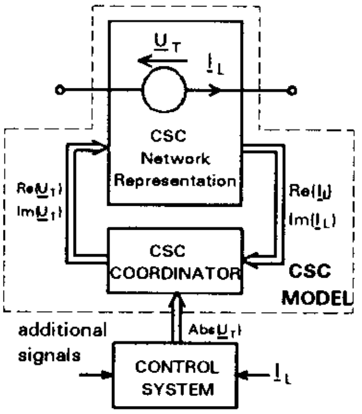


Figure 3.29: GTO - CSC model

The UPFC is able to control three parameters: amplitude and phase angle of the voltage $\underline{U}_T$ in the series branch and the voltage $\underline{U}_A$ on the terminal of the shunt branch using the reactive power control of the shunt GTO converter (Fig. 3.30). The series branch voltage $\underline{U}_T$ that is injected can be in any phase with respect to $\underline{U}_A$ and can have any magnitude from 0 to the maximum value U_{Tmax}. The operating area becomes the region limited by a circle with radius U_{Tmax}.

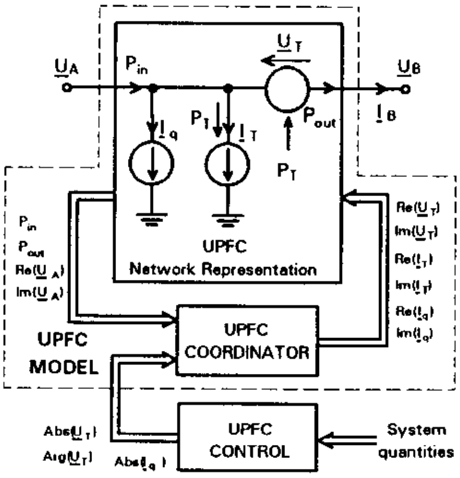


Figure 3.30: UPFC model

The operating point can be continuously changed (continuous change of $\underline{U}_T$ phase and magnitude). The component of the voltage $\underline{U}_T$ which is in phase with the current

$\underline{I}_B$ represents the real part of the injected power. It is provided by the UPFC parallel branch (current $\underline{I}_T$). The component of the voltage $\underline{U}_T$ which is perpendicular to the current $\underline{I}_B$ represents the reactive power component. It is generated internally and is independent of the real component. The injection of the active and the reactive power by the series branch of the UPFC can be denoted as the result of voltage $\underline{U}_T$ injection.

Assuming that the UPFC is not connected directly to a stiff voltage source then, additionally the voltage of the UPFC shunt transformer terminal can be controlled via the reactive parallel branch current $\underline{I}q$.

3.5.2.2 Description of the System and Simulation

A study on the use of FACTS elements for load flow control in a meshed system in steady state and transient conditions has been conducted using the 400 kV system in Fig. 3.31. The network is a simplified model of an existing system. The system consists of two meshed subsystems (S_I and S_{II}) which are connected by two double-circuit lines with a length of 360 km (lines A-B and C-D). In each subsystem there is a total generation of 3600 and 3900 MW, respectively.

The generation is composed of typical units of nuclear power plants and thermal power plants. The voltage, frequency and power control including power system stabiliser are included in the model.

In this basic situation a load of 200 MW should be transmitted from system S_{II} to system S_I. But in this configuration an undesired loop flow of approximately 200 MW occurs as shown in Fig. 3.31.

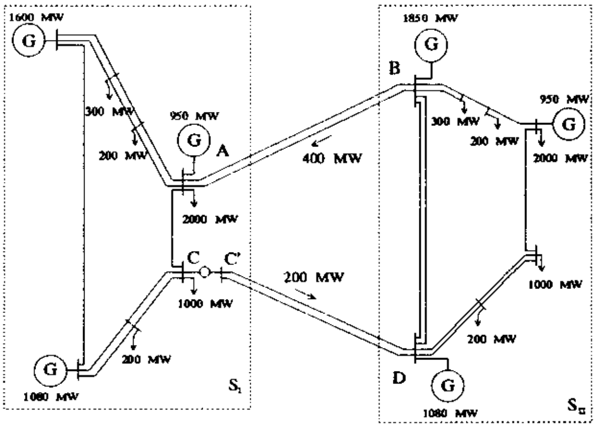


Figure 3.31: Test system

In order to improve the steady state and also the dynamic behaviour of the complete system, three different FACTS devices were positioned at node C in the connection C-D (see Fig. 3.31). The main tasks of these devices were:

- minimisation of the active power flow in the loop;
- minimisation of the reactive power flow in the lines C-D to reduce losses (if possible).

Besides the reactive and active power flows in both connections A-B and C'-D, Fig. 3.32 also shows the magnitudes of the control voltages U_T, necessary to control the active power loop flow to zero for each FACTS device, respectively. Calculations have been made using a steady state control of the FACTS equipment starting with system conditions without FACTS load flow control. Configuration of the used system leads to the conditions close to example B in Fig. 3.26.

3.5.2.3 Action of the Quadrature Boosting Transformer

As shown in Fig. 3.32a, the phase shift of the voltage phasors caused by the QBT results mainly in a change of active power flow in the line C'-D. Using an injected voltage of about 0.25 P.U. of the rated phase to ground voltage enables the complete suppression of the active power loop flow in the system. Additionally, in the line C'-D, the reactive power flow changes also, mainly as a consequence of the fact that in the case of QBT action QBT terminal voltage magnitudes also change.

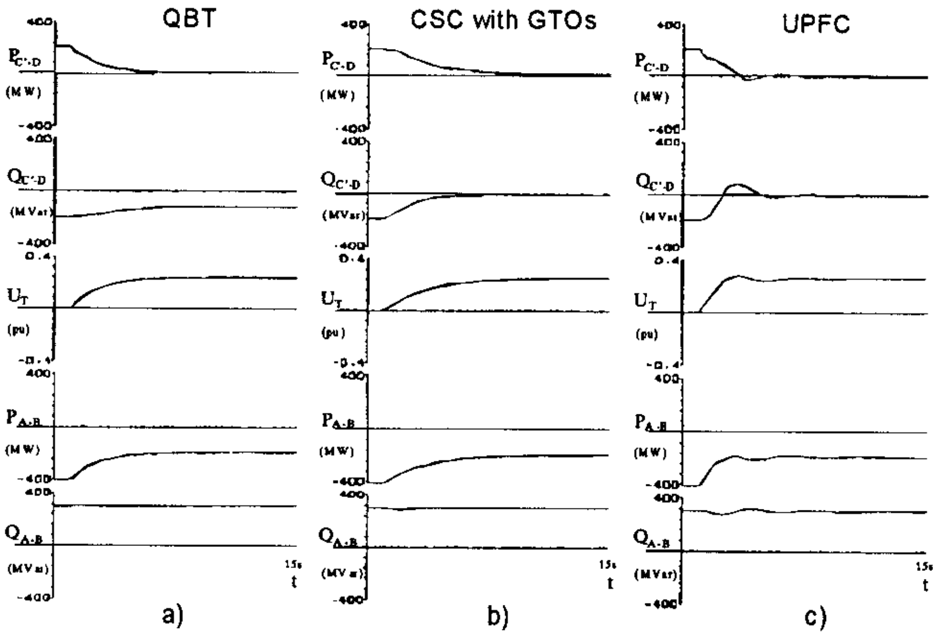


Figure 3.32: Power flow control in lines C'-D of the system in Fig. 3.31
a) QBT
b) CSC with GTO
c) UPFC

While the active power flow of the line A-B is changed by the controlled loop flow amount (200 MW), the reactive power flow changes only slightly, because the voltage magnitudes of the line terminals are controlled by infeeds of power plants.

3.5.2.4 Action of the GTO-CSC

The CSC using GTOs can be considered as a voltage injected serially into the transmission line. The phase of this voltage is perpendicular to the line current, so it also acts as a current dependent reactive impedance. With CSC using GTOs it is theoretically possible to suppress the active and reactive line power flow close to zero (Fig 3.32b). In reality some small line current continues to flow. The change of active and reactive power can not be controlled independently. The active power flow through the line A-B changes by the amount of the controlled loop flow, while the reactive power flow in this line does not change significantly.

3.5.2.5 Action of the Unified Power Flow Controller

A UPFC has three independent controllable parameters of which two are needed for load flow control. As shown in Fig. 3.32c, both active and reactive power flows in line C'-D can be controlled to zero. To achieve this desired effect, two UPFC controllable parameters (i. e. phase and magnitude of the injected voltage U_T) are controlled. Although the final effect is similar to the one obtained with the CSC using GTOs, physically it is different. While in the case of CSC using GTOs, active and reactive power are dependent, in the case of the UPFC the active and reactive power flow are controlled simultaneously and independent of each other. As is the case with the CSC using GTOs and the PAR, the active power flow in the line A-B changes by the loop flow amount and the reactive power flow in this line remains almost unchanged.

4. Impact of FACTS Controllers on Load Flow and Stability

In this chapter different studies are presented which illustrate a variety of problems that can occur in transmission/distribution systems and the possible advantages afforded by the use of FACTS controllers. It is typical that different system configurations and different goals for load flow control lead to different FACTS controllers. The selection of the best equipment for a given system should consider different controllers at different locations.

4.1 Use of FACTS Devices to Improve Power Flow in Interconnected Systems

4.1.1 Introduction

The following example of application of FACTS devices has been based on a model drawn from a real 400 kV transmission system. The network has a very meshed structure with power plants distributed and close to the load centres; the average transmission distance is relatively small (50 km).

The studied network does not normally experience transient stability or oscillatory problems [13], [14], because of the highly meshed structure (high short circuit power) and the damping effect provided by PSS on generator voltage regulators.

As the overall transmission is mainly performed by a unique voltage level with lines of uniform characteristics (i.e. the ratio X/R of the lines is nearly the same), the natural power flow distribution without any load flow control usually implies minimum power losses in the system.

4.1.2 Application of FACTS Controllers

The use of FACTS controllers has been considered in order to accomodate different network conditions from those planned (in both technical and economic senses), and in particular:

- security functions to avoid thermal and voltage constraints in case of severe contingencies;
- power flow control in order to exploit the existing transmission capacity to import low cost energy available in other countries without any reinforcement to the existing network.

For the given network structure, the parameters and the planned development of an actual transmission network concerning different countries, realistic power and load dispatching have been assumed and a power flow calculation has been performed. Attention has been paid on a specific area of this network. General ideas on possible advantages for the network operation with FACTS devices in terms of static adequacy can be drawn from this analysis along with an economic estimation based on certain hypothesis on production and device costs.

In particular, application with a PST (Phase Shifting Transformer) device has been examined as no need for fast load flow control existed.

The first scenario (figure 4.1) considers the existing system of interconnection lines, in which the southern path is constituted by a single-circuit line with relatively low transmission capacity. The power flow distribution (active power in MW) corresponds to the maximum import condition for which the network is operated in a secure state. The limiting condition (according to usual planning criteria) is the outage of one circuit of the northern interconnection (AL-RO), bringing the southern interconnection near to the thermal limit (line VE-PI).

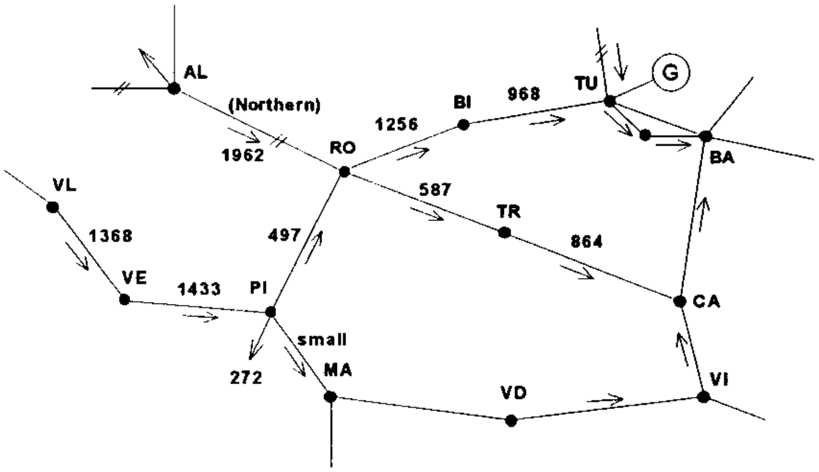


Figure 4.1: Power flow [MW] for maximum import (no FACTS)

A different operating condition with increased power import is assumed to substitute internal "high cost" production. In this case some lines along the southern path are heavily loaded even under normal conditions (figure 4.2); overloads can appear in case of some contingencies.

A more secure operation may be achieved if a FACTS controller is adopted on the internal line PI-RO. The primary goal of the device is to limit transfers on the southern interconnection by forcing power to flow through the more robust northern interconnection, thus maintaining the system operation within thermal limits.

The reference case considers a 10° phase shifting PST (corresponding to about a 350 MVA rating), with 800 MW decrease of internal production (located at the TU node). Power flow distributions corresponding to partial and full PST action are shown in figure 4.3 and 4.4 respectively.

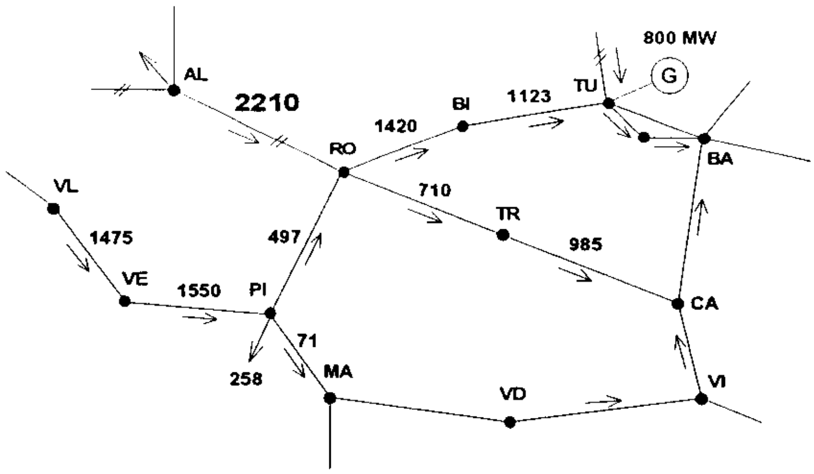


Figure 4.2: Power flow [MW] with increased import (no FACTS)

The selected rating (350 MVA) for the FACTS device has been drawn from the maximum current acceptable for the line (thermal limit of about 2.8 kA) even if in the considered application the current experienced by the line is lower. This choice guarantees the use of the PST in all the network conditions, allowing the control of possible overloads.

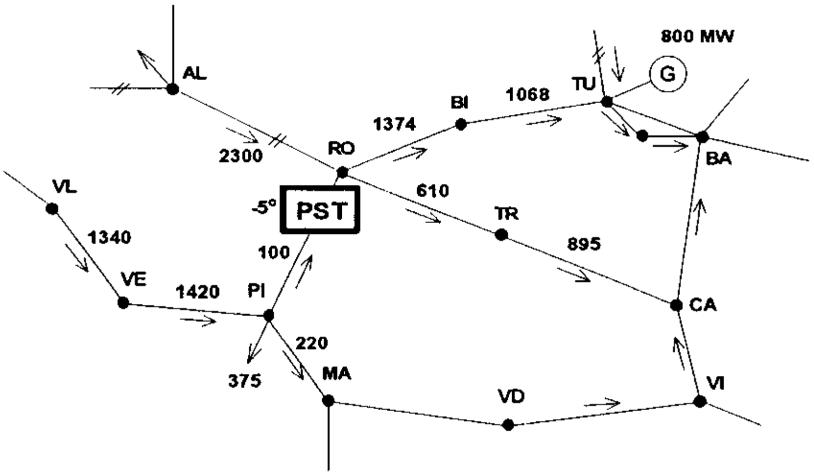


Figure 4.3: Power flow [MW] with increased import (PST on internal line)

The sharing between the northern and southern paths of the 800 MW total power import increase (disregarding losses) is as follows:

Without any flow control (figure 4.2, insecure operation) :

northern connection : +260 MW
southern connection : +120 MW

With the FACTS device in partial operation (i.e. not exploiting the full angle capability) in order to gain secure conditions (figure 4.3) :

northern connection : + 350 MW
southern connection : unchanged

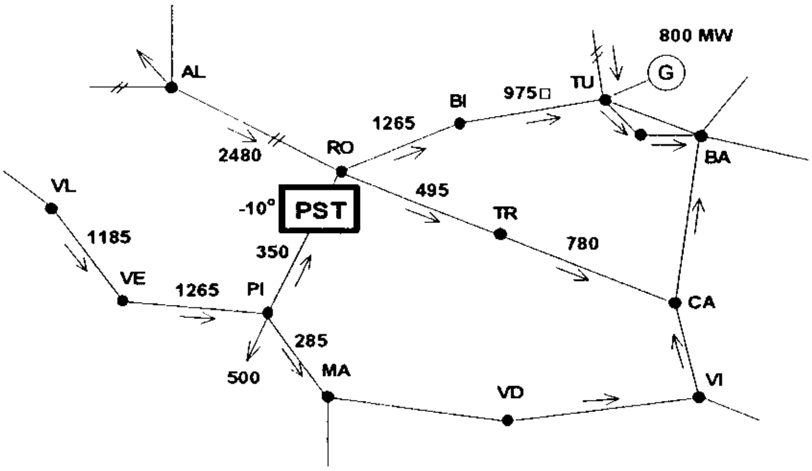


Figure 4.4: Power flows [MW] with increased transfer (PST with maximum control angle on internal line)

With the FACTS in full operation with 10° phase shifting (figure 4.4) :

northern connection : + 530 MW
southern connection : - 170 MW

the remaining power being transferred through other interconnection lines.

The FACTS controller has a twofold effect:

- to assure adequate operation of the network
- to control the sharing of the power import between the two considered interconnections.

4.1.3 Economic Considerations

a) The substitution of internal high cost production by imports of cheaper energy permits savings that must be analysed on a case by case approach. The amount of import permitted by unused existing capacity of the network, duration of the import and differences between the two production costs are the parameters that should be considered in order to determine the convenience of FACTS option. In the considered example, a rough estimation of 2.5 % saving per year was obtained that should be compared with the annual costs of FACTS option and corresponding additional losses. This was for a total internal production of about 40 GW and for the cost ratios :

$$\frac{C_{imp}}{C_{base}} = 0.9; \qquad \frac{C_{peak}}{C_{base}} = 2.0$$

where C_{imp} is the cost of the imported kWh, C_{peak} is the cost of the internal expensive production, C_{base} is the mean cost of internal base conventional production.

b) The example given concerns the power shifting between two interconnection paths with different neighbouring countries. This can be also used to exploit different energy prices of the imports.

With reference to the previous network structure, technical and economic evaluation of the overall convenience to adopt a FACTS device has been analysed.

Two transmission paths (northern and southern connections in figure 4.1 and 4.4) are usually loaded under normal conditions (natural load flow) according to the natural distribution due to the line impedances.

By using the FACTS capability to control power flows along the two paths, a wheeling of power of about 275 MW can be forced to the northern interconnection by relieving of approximately the same amount the other path. In case of a difference in the costs of spot energy imports (as the case with large interconnected networks having different generation types and power surplus) , the application of FACTS options could permit to pay its investment and additional losses costs.

For a preliminary economic evaluation, the following assumptions have been made:

- a depreciation period of the FACTS investment of 15 years (due to the fast obsolescence of the technology, and relatively high losses of the FACTS device);
- investment costs of a FACTS device (Advanced GTO-based Static Phase Shifter) - 350 MVA - about 50 MUSD [13]. This cost refers to a prototype with all the development and testing costs included. Of course, for industrial technology the economic estimation could result in a better figure.
- c1 [USD/MWh] is the cost of the energy imported along path 1 in the considered example (the cost along path 2 has been supposed equal to that of internal production c2);
- internal generation cost (c2) of about 22 USD/MWh ;

- imported energy cost along path 2 equal to the internal generation cost c2;
- import duration of 2500 hours per year (utilisation period of the FACTS device).

The cost functions relevant to the different power imports by varying the ratio c1/c2 are shown in figure 4.5. The difference between the two curves represents the saving function showing the economic convenience of utilising the FACTS options.

The break-even point corresponds to the balance between the annual cost and savings permitted by the FACTS device. For this application, it has been found about (c1/c2)=0.7. This result could be attractive due to the fact that such an energy cost ratio seems achievable.

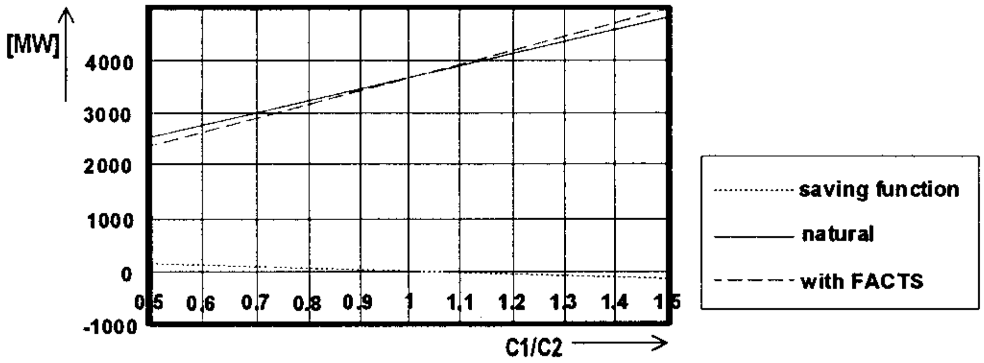


Figure 4.5: Cost functions vs. C1/C2 ratio

4.1.4 Conclusions

General ideas on possible advantages for the network operation with FACTS devices in terms of static adequacy has been drawn from the analysis on a meshed transmission system. An economic estimation based on certain hypothesis on production and devices costs has been derived.

It has been shown that FACTS options can accomodate unpredictable conditions caused by delays on the development of the planned network and also allow the exploitation of unused transmission capacity to increase power exchanges between countries. The latter aspect could represent an attractive possibility in order to permit in the future higher power exchanges in large interconnected transmission systems between countries.

4.2 Load Flow Control in a Complex Interconnected Network.

4.2.1 Introduction

This is a comparison of the effectiveness of the Phase-Shifting Transformer (PST) and the Series Compensation (CSC) in the case of a possible application to improve the performance of a complex interconnected power system. The basic data used in this work represents the Balkan section of the UCPTE system taking into account the parallel synchronous operation with the Bulgarian System [15, 16, 17].

The test system is divided into five subsystems: A, G, B, F and J, interconnected via eight transmission lines as show in figure 4.6. Main data of the subsystems are shown in Table 4.1.

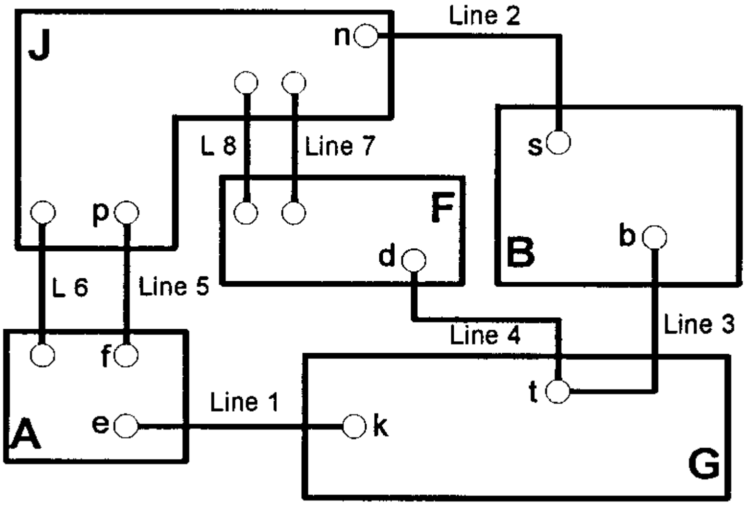


Figure 4.6: System configuration

System	Installed Power MW	Transmission Voltages (kV)	Network Nodes
A	1892	220/110	12
G	9232	400/150	39
B	12074	400/220	51
F	780	400/220	6
J	21348	440/220	120

Table 4.1

In the past, load flow and voltage-level calculations have been undertaken to demonstrate the feasibility of the synchronous interconnection of subsystem B with UCPTE following multilateral agreements by the power utilities involved [18]. Studies have examined realistic scenarios for large power exchanges in cases of generation shortfall in any of subsystems and have determined the limiting factors for such exchanges. Also, the problem of unscheduled loop power flows between subsystems during zero power exchange has been recognised.

Line	Ratings kV	 MVA	Length (km)
1	400	675	190
2	400	1300	163
3	400	1300	175
4	400	1300	115

Table 4.2

Four of the eight interconnecting transmission lines are emphasised with their parameters being given in Table 4.2. Line 1 is of interest because it is associated with a bottleneck effect due to a 400/220 kV autotransformer at node e, while, the state of protection of the lines 2, 3 and 4 determines the upper limit of power interchange.

4.2.2 Study Objective

The aim of the present work is to compare the effectiveness of two different types of FACTS controllers, the PST and the CSC, on load flow control and contingencies affecting the interconnections.

The control of power flow over the interconnecting routes is important since the interconnected system includes five independent utilities.

The ability of the systems to continue to supply demand following major outages is, also very important. A simple but sufficiently accurate analytical relationship is proposed, to determine the parameters of PST or CSC to achieve the required active power exchanges.

The interconnected system has been represented in a load flow program. The modelling of the PST and CSC is done by modifying the electrical parameters of the network. Accordingly, the PST case is dealt with by using the Y_{bus} - modifying model [19], while the CSC is represented by the modified line reactance, expressed in terms of degree of series compensation, $X\ (1\text{-}K_{se})$.

4.2.3 Cases Considered and Results

The first case (case a) is the scheduled zero power exchange between subsystems. In this case 112 MW flows from G to A through line 1 and flows back to G via F through line 4 (93 MW) and via B through line 3 (19 MW). If a PST (or PAR if dynamic control is needed) is installed on line 1 and is set at phase-shift angle α = 10°, then, the loop load flow is reduced to 33 MW (from G to A through line 1).

In the case b a large system power exchange program is considered. From system J 990 MW are exported to B and 500 MW to system G. Figure 4.7 shows the variation of the active power delivered by the line 2 to system B when a PST is applied on this line, as a function of the phase-shift angle α Figure 4.8 shows the variation of the active power delivered by the line 2 to system B, when CSC exists in the line, as a function of the degree of series compensation K_{se}.

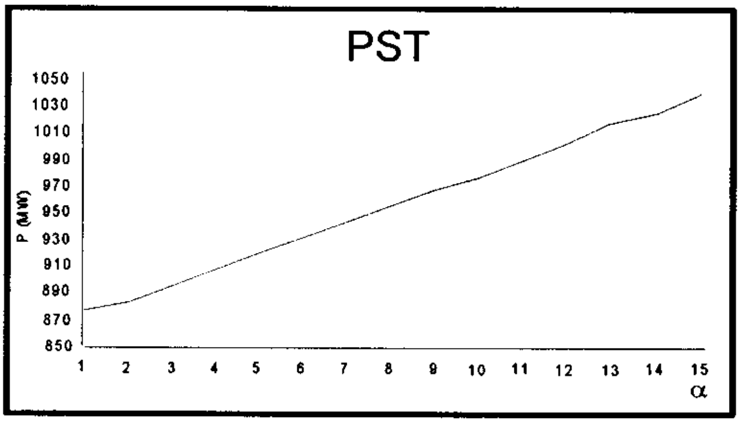


Figure 4.7: Variation of active power in the line 2 when PST is applied on this line

It was found that the parameters of PST and CSC, assuming their effect on the active power through the line are approximately the same, are related with the following approximate equation [16]:

$$K_{se}=1-(1+X_t/X_{ij})/(1+tg\alpha/tg\delta_{ji}) \qquad (4.1)$$

where X_{ij} is the line reactance, δ_{ij} is the phase angle difference of the voltages at sending-end and receiving-end of the line, and X_t the reactance of the PST.

For the case b we now assume the tripping of line 4. Then line 2 becomes overloaded by roughly 1%. When a PST is installed on line 2 with phase-shift angle α.=-10°, the redirection of power flow results in a condition in which there are no lines overloaded (the load of line 2 is reduced by 101 MW).

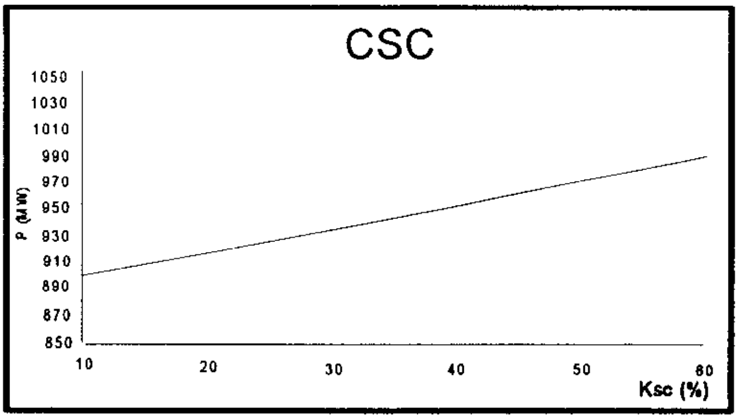


Figure 4.8: Variation of active power in the line 2 when CSC is applied on this line

Case c considers another large power exchange condition in which subsystem G exports to subsystems J and F 400 MW and at the same time exports to B 400 MW. The tripping of line 3 has been assumed. In this case, the autotransformer at node e receives 337 MW and is overloaded by 12%. If a PST is installed on line 4 and is set at phase-shift angle α= 10°, then, the autotransformer is loaded with just 273 MW, and no overloaded elements can be found in the system.

Referring to case b and assuming power flow control by means of either a PST or by CSC, which we presented in Figures 4.7 and 4.8, we can calculate [17] the necessary ratings of PST (in MVA) and CSC (in MVAr) and subsequently we can determine the power flow control efficiencies of PST and CSC (ratios of the redirected power flow over the controller rating). Then, based on unit costs of the two alternatives we can estimate the costs of equipment per MW of power flow control capacity. It is found that the PST is more economic than the CSC [17].

4.2.4 Conclusions

A comparison has been made of the effectiveness of the steady state load flow control of PST and CSC. The power flow redirection properties of the PST (or PAR) were shown to be superior to those of CSC. A simple but sufficiently accurate analytical relation connects parameters of PST and CSC for equivalent active power redirection effects. The positive effects of using PST in achieving suitable power flows in post dynamic states resulting from the tripping of major interconnecting power lines and in maintaining steady state security whilst realising large power exchanges were seen. The PST appears, to be the advantageous choice over the CSC.

4.3 Link Between Synchronous Subnetworks Without Increase of Short-Circuit Currents

4.3.1 Introduction

The purpose of this example is to demonstrate the application of the Interphase Power Controller (IPC) technology as a means of providing an interconnection, without transferring perturbations between two synchronous subnetworks.

Figure 4.9 illustrates the networks of two electric utility companies A and B within a large interconnected system. A large combined-cycle unit is commissioned in B and surplus energy is to be exported to A. Both networks operate at the same nominal voltage but:

- the earthing on both sides is different, direct in A and resonance-earthing in B;
- the phase-shift and the voltage difference between A and B makes a direct connection impossible.

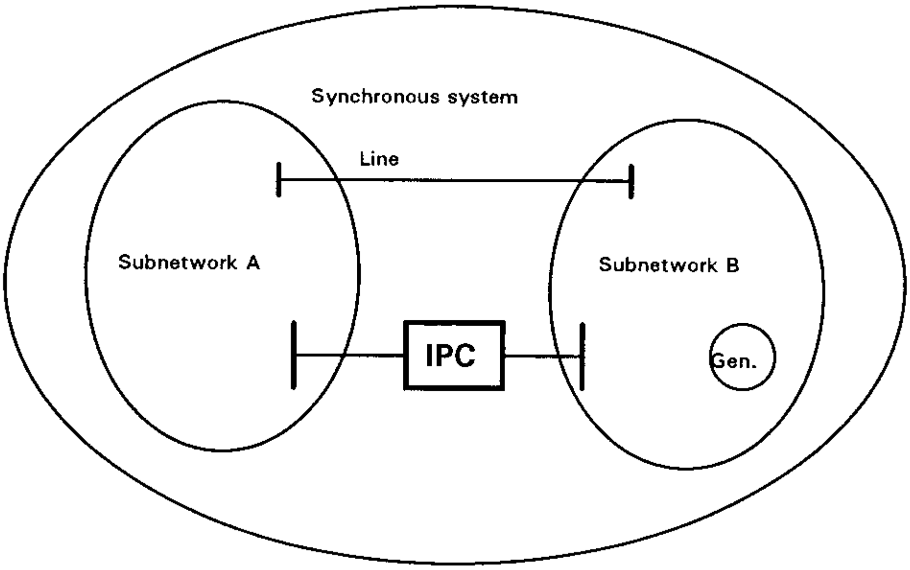


Figure 4.9: IPC link between synchronous subnetworks

Solving this interconnection problem with traditional technology implies the use of a phase-shifting transformer. However such a solution would provide synchronous coupling detrimental to the operation of both systems.

The Interphase Power Controller can resolve this problem more completely. The principal features of the IPC are illustrated in the example:

- for a constant setting, the power through the IPC remains practically constant, whatever the network conditions;
- the decoupling effect associated with the IPC avoids transfer of perturbations from one system to the other (in particular, earthing methods do not interfere with each other).

The first topic is illustrated by the behaviour of the system following the loss of the combined-cycle unit (400 MW). The second one is illustrated by considering the consequences on both sides of the IPC of a short circuit in one of the subnetworks.

4.3.2 Loss of Generation

The first curve of Figure 4.10 shows the active power through the IPC following the trip of the generating unit. The second curve gives the flow in a remote line linking the same subsystems. Because of its inherent power flow control characteristic (see Section 3.4.7), the IPC maintains the interconnection power practically constant.

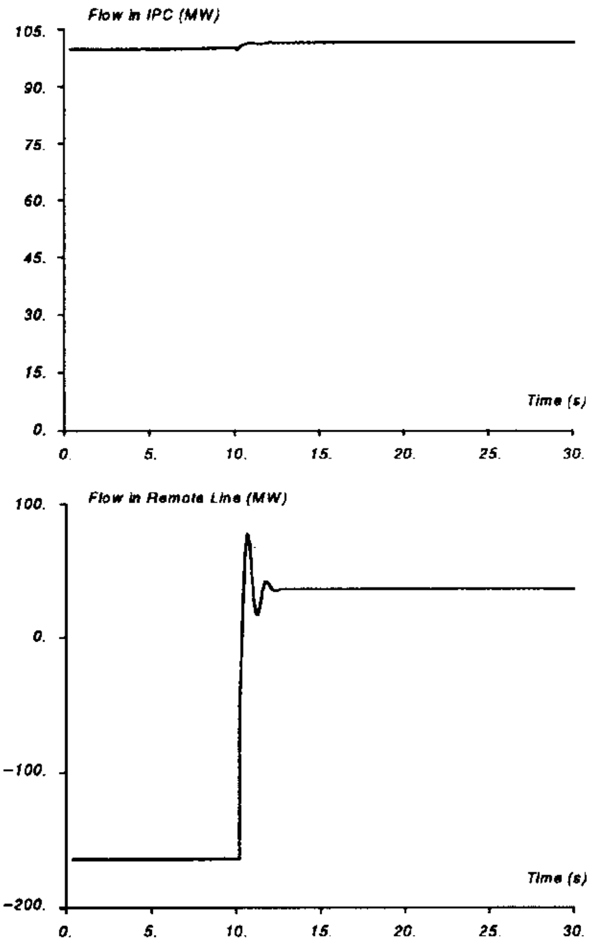


Figure 4.10: Power flows following loss of generation

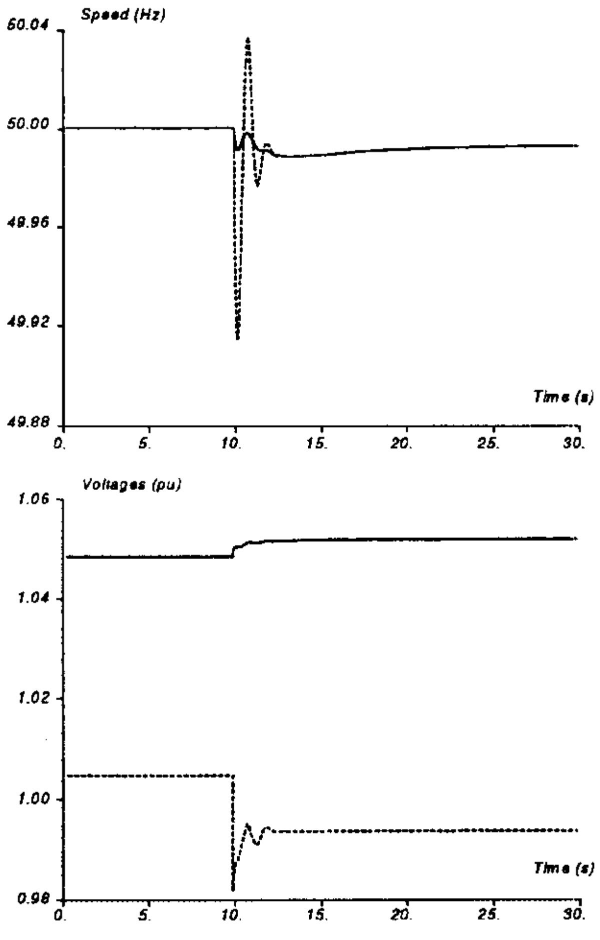


Figure 4.11: Generator speeds and network voltages following loss of generation

For the same incident, the first set of curves in Figure 4.11 show the speed of two generators, one in network A (continuous line) and one in network B (broken line). This second generator is affected by the loss of the large unit in the same subnetwork but the impact in the other network is almost negligible. The second set of curves in Figure 4.11 shows corresponding voltages in A (continuous line) and in B (broken line).

4.3.3 Short Circuit

A three-phase short circuit affects system B not far from the IPC. Figure 4.12 shows the voltages and currents on both sides of the IPC:

a) the voltage on the B-side (first curve) falls to almost zero because of the fault;
b) the current on this side, remains quite constant;
c) the voltage on the A-side is practically unaffected;
d) the current on this side (fourth curve) falls to a small value during the fault.

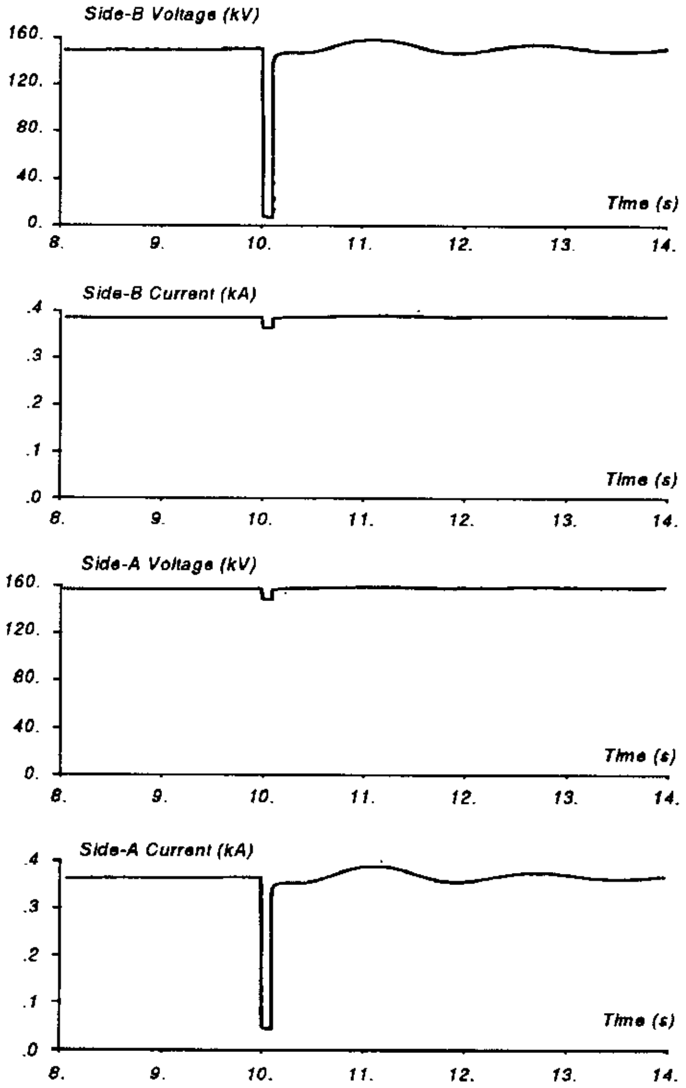


Figure 4.12: IPC voltages and currents for a fault in network B

These results demonstrate the voltage-dependent current-source behaviour of the IPC. Indeed, the contribution to the fault from the IPC remains almost equal to the initial load current. It is slightly reduced because of the small drop in voltage on the A-side which sees the remote fault because of the parallel line. In the A network, there is a momentary reduction in the current during the voltage depression on the B-side. This is more acceptable than the large overcurrent that would have been experienced with the conventional phase-shifting transformer solution.

4.3.4 Synthesis

The results above demonstrate the decoupling effect of the IPC for two severe perturbations. Since the IPC is a passive device, it does not affect the dynamic behaviour of the interconnected system. This behaviour is desirable of interconnections for energy contracts, where synchronising and damping powers are not an issue.

4.4 Enhancement of First Swing Stability of Large Power System

4.4.1 Introduction

The effects of different FACTS devices (shunts and series devices, and static phase shifters) on the transient stability of a large power system (first swing stability) are studied.

The study is broken down into two sections. The first identifies the most interesting FACTS devices in reference situations using theoretical considerations like the "equal area criterion" [20] validated by means of simulations of the reference situations. The second was used to study in more detail the effect of series compensation on a real scenario from the French power system, and the optimum control parameters for series FACTS devices for problems of transient stability.

4.4.2 Studies of Reference Situations

The analysis consisted in determining the critical clearing time for faults using a simplified "equal area criterion" type approach and simulations. The power system used is given in Fig. 4.13 is a simplification of a possible system configuration, with a generator feeding into a high-power system. The FACTS devices intended to be used in this part are the shunt FACTS devices (SVC and SVG), series FACTS devices (variable series capacitor: TCSC), and the phase angle regulator (PAR).

The principles of how the FACTS devices operate on the power system have already been established [21], [22], [23]. The originality of this approach lies in the study how the capacity and dynamics of FACTS devices effect the critical clearing time for faults in order to determine how useful the devices are.

4.4.2.1 Reference Situations

The reference situations adopted are power systems consisting of a reduced number of generators and power lines. A series of scenarios was drawn up for each of the types of phenomena to be studied: active power flow problems, voltage stability problems and transient stability problems.

Figure 4.13 shows the layout used to study transient stability.

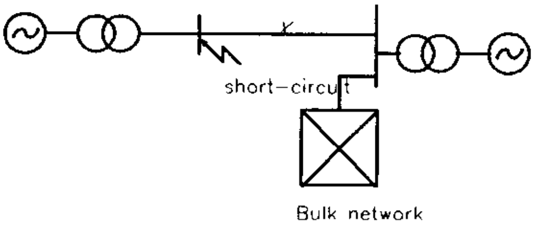


Figure 4.13: Reference situation for studying transient stability

This diagram represents a generating site connected to the rest of the power system by a power line with impedance X. It supplies a power of P_m to the power system which has a maximum transmission power $P_{max} = U^2/X$ (where U is the voltage at both ends of the line). The ratio P_m/P_{max} shows how well the grid withstands short-circuits and the stability margins decrease as P_m tends towards P_{max}.

Hereafter, an example is used to compare the effectiveness of the different types of FACTS. The hypotheses are set out below:

$P_{max} = 6600$ MW (i.e. $X = 24.2$ Ohms)
$P_m = 5950$ MW (i.e. $P_m/P_{max} = 0.9$)
Apparent power of the site: 6600 MVA

The critical clearing time for faults is 50 ms (base scenario without FACTS devices).

4.4.2.2 Shunt FACTS Devices

Figure 4.14 shows the extent to which the rating (Q_{max}: maximal reactive power at rated voltage) effects the critical clearing time for faults for the different values of the ratio P_m/P_{max}. These curves are independent of the voltage and the length of the line and can therefore be considered extremely general. The results were obtained using calculations of the equal area criterion type.

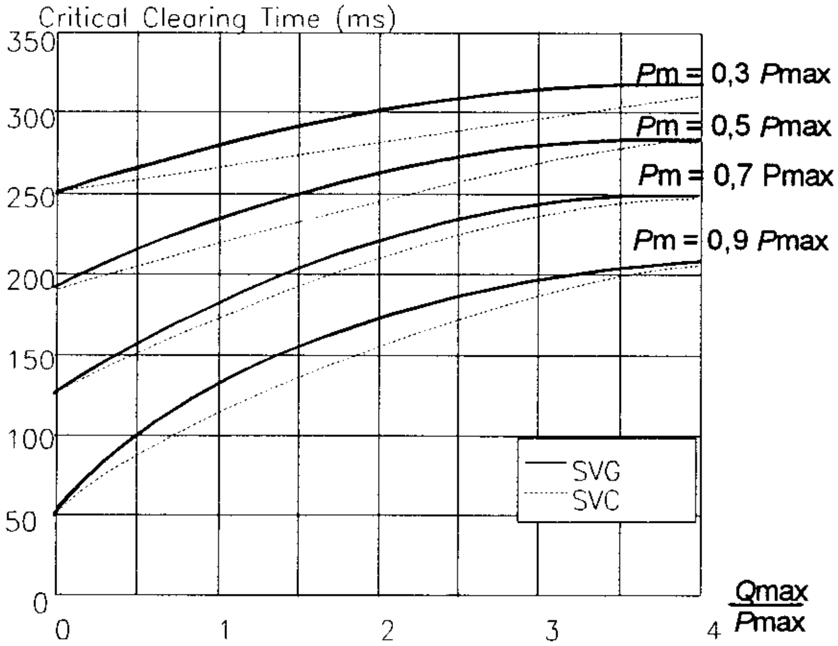


Figure 4.14: Effect of SVC and SVG rating on the critical clearing time.

Use of curves:

> Should one wish, in the above hypotheses, to increase the critical clearing time to 130 ms, an 8250 Mvar SVC (Q_{max}/P_{max} = 1.25, read from the curve), or a 6600 Mvar SVG (Q_{max}/P_{max} = 1, read from the curve) would be necessary.

It can be noticed that in this situation the SVG is 25 % more efficient than the SVC.

It has therefore been shown that shunt type FACTS devices are a useful solution, but the power ratings must be very high.

These results were validated using simulations which showed the importance of the response times for these shunt type FACTS. These dynamic characteristics, which depend on the performance of controls, alter the results moderately. Indeed, if the control cannot deliver the available Mvar sufficiently rapidly, the FACTS devices will not be able to achieve the expected critical clearing time.

4.4.2.3 Series FACTS Devices

The curves in Figure 4.15 show changes in the critical clearing time for faults in terms of the power line compensation ratio of the CSC for different power transmission values. The compensation ratio is the ratio of the impedance of the series capacitor to the impedance of the power system seen from the generator.

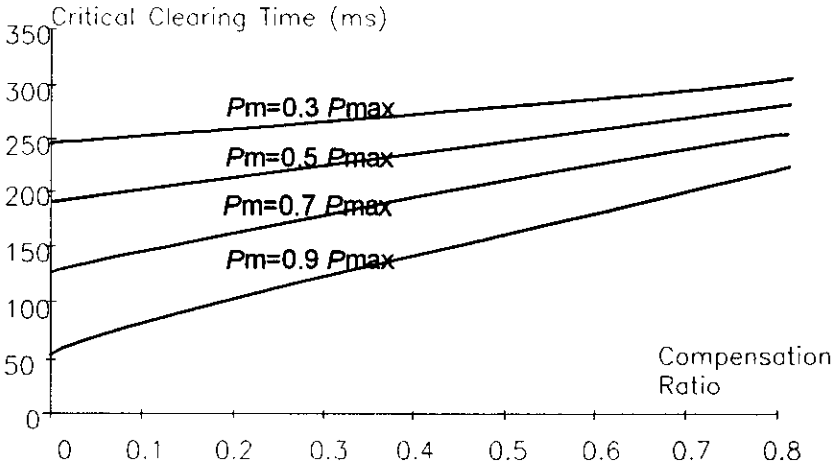


Figure 4.15: Effect of a CSC rating on the critical clearing time.

If we reconsider the previous example, it can be seen that a 2300 Mvar series FACTS device (i.e. compensation ratio of 35%, read from the curve) is needed.

As with the shunt FACTS, validation by means of simulations showed the effect of dynamics on results. The control should also be able to deliver the available Mvar as quickly as possible.

Series compensation is therefore an effective means compared with shunt type FACTS to improve the transient stability. In order to be effective, the series FACTS do not need to have a high power rating.

4.4.2.4 Phase Angle Regulator

Figure 4.16 shows the changes in critical clearing time for faults in terms of maximum phase shifting for the phase angle regulator for different values of the P_m/P_{max} ratio.

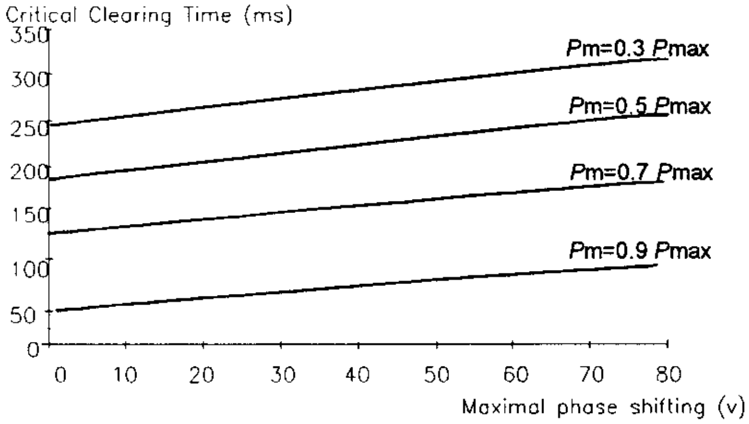


Figure 4.16: Theoretical Effect of a Phase Angle Regulator rating on the critical clearing time.

The effect is slight for a reasonable power rating device, and the control proved difficult to implement.

Indeed, in the chosen example, the phase angle regulator must have a rating of 13200 MVA (i.e. 195° phase shifting, which lies outside the range of the curve shown). This shows that the PAR is not effective for first swing stability.

4.4.3 Situation in Power System

This study of a real power system is a continuation and extension of the previous studies into the basic behaviour of series FACTS devices identified as being potentially the most useful. The intention is to evaluate the impact of variable series compensation on the transient stability of the French power system by comparing it to the fixed series compensation, which appears at first sight to be the most cost-effective. The target region is a generating site where the stability limits will be fairly strict by the year 2010 as regards certain power system development assumptions.

A diagram of the region under consideration is given in Figure 4.17, which is a more detailed representation of figure 4.13. The study covered the entire French transmission system.

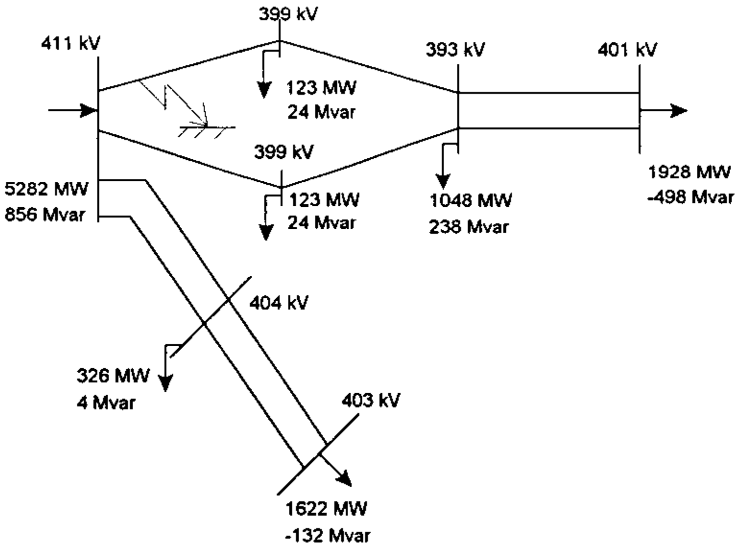


Figure 4.17: Simplified diagram of the region

This study confirmed the relative advantages and disadvantages of fixed and variable series compensation faced with transient stability problems, with the following observations:

- In the present case, where the enhancement of stability limits would require a great deal of compensation, fixed series compensation, although extremely interesting for stability problems, causes voltage and power flow problems, and can raise problems as regards the protective relays of the lines.

- Variable series compensation therefore seems an interesting alternative. Furthermore, assuming it is not active during normal mode, and only active during disturbances, it will not cause problems with the voltage or power flow, and has only a slight effect on the protective relays.

4.4.4 Synthesis

On the basis of the reference situations, increasing the critical clearing time from 50 ms to 130 ms, with a maximum transmissible power of 6600 MW and a generated power of 5950 MW, would lead to the following FACTS apparent power ratings :

- PAR	13200 MVA
- SVC	8250 Mvar
- SVG	6600 Mvar
- CSC	2300 Mvar

The conventional series compensation is also a solution for increasing the transient stability. This solution is certainly more cost effective than a CSC one. However, a study on a real power system has shown that the fixed series compensation can cause some voltage and power flow problems, which would not occur with variable series compensation.

4.5 Power Oscillation Damping in a Meshed System

4.5.1 System Configuration

In sec. 3.5 the possibility of using FACTS devices to control power flow in an interconnected system consisting of two subsystems in quasi-steady-state conditions was described. As presented, the load flow control is fast enabling also the improvement of the system behaviour during electromechanical dynamic phenomena. In this chapter a comparison is made of the effect of various FACTS devices on power oscillation damping.

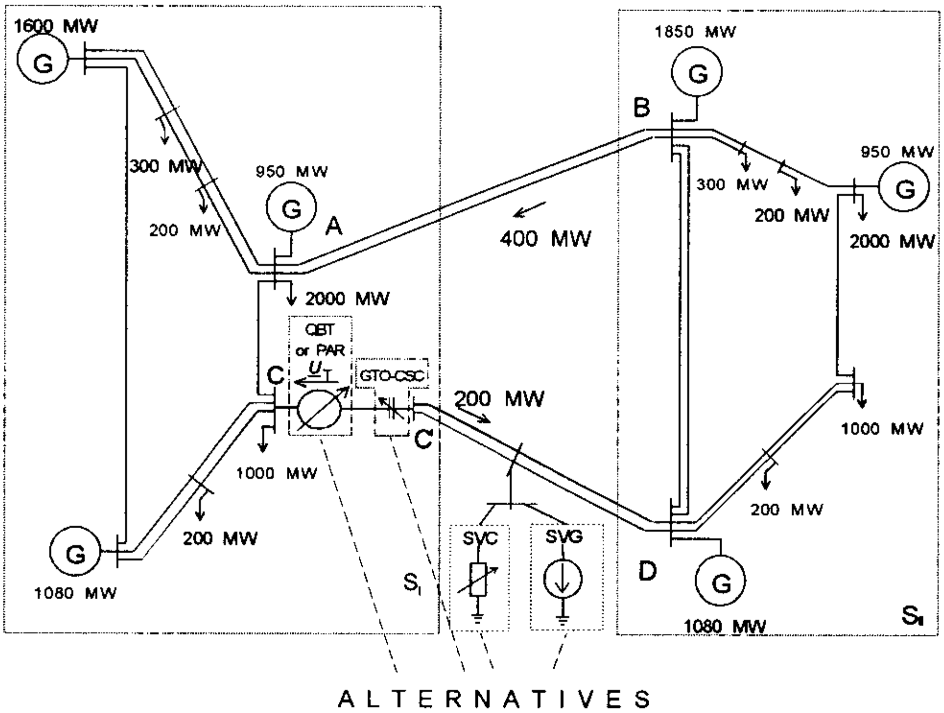


Figure 4.18: System configuration

The system configuration examined is shown in Fig. 4.18. and is described in sec. 3.5.2. In addition to that system and the previously discussed series connected FACTS devices, parallel controllable compensation is included as an alternative in the middle of the connection between nodes C and D (c.f. Fig. 4.18).

If 3-phase fault occurs on the line between nodes A and B and is followed by the line tripping of the faulted line within 100 ms, Fig. 4.19 indicates that the system is stable for the above mentioned fault with the additional interconnection (between nodes C and D). However, power oscillation during the transition into the new steady state condition after tripping one line between A in B is poorly damped. The aim of the study was to improve damping of the presented system by including FACTS devices so as to shorten oscillation period to about 40% of its duration when no FACTS devices are implemented to damp oscillations.

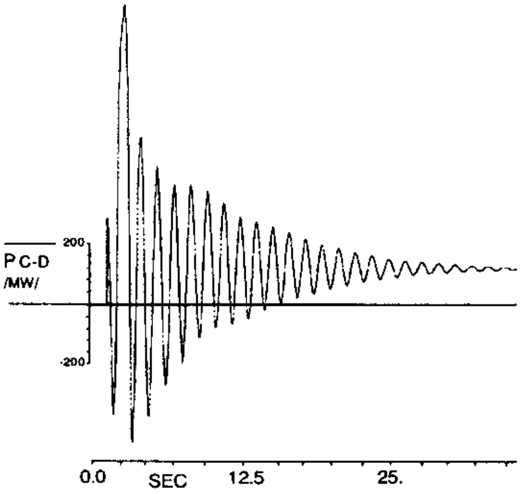


Figure 4.19: Active power flow after 3-phase fault near node B.

4.5.2 Simulation

Modelling and a digital simulation are carried out in the stability mode of the NETOMAC program. FACTS devices are modelled as described in sec. 3.3 and sec. 3.5.2.

In this work the pre-fault state is "controlled load flow-state" described in sec. 3.5, i.e. real power flow in the lines between nodes C and D equals zero. In the instance of fault occurrence the devices used for controlling load flow (GTO-CSC, PAR, QBT) are taken into account. Damping of power oscillations is carried out with the same type of device as it is implemented for steady-state load flow control before the fault with the exception of the parallel compensation (SVC, SVG). These latter two devices have a minor impact on real power flow in the line between nodes C and D thus they are inappropriate for steady-state load flow control. In the cases when an SVC or SVG are implemented for power oscillation damping the pre-fault load flow control is carried out with additional phase angle regulator.

The power oscillation signal used by FACTS controllers is the line real power time derivative dP_{CD}/dt which can be derived from local system quantities. In order to minimise the ratings of the FACTS devices the power damping action is delayed for about first two power swings.

Results of the digital simulations are presented in Fig. 4.20. The rating of the various devices is chosen so as to achieve nearly the same damping effect (power swings should be damped in about 10 seconds). In the case of FACTS devices using the physical principle of voltage injection (GTO-CSC, QBT, PAR) the presented quantities are the line real power as well as the injected voltage magnitude U_T (or phase shift) and throughput power. In the case of parallel compensation (SVC, SVG) the line real power and the device reactive power are presented.

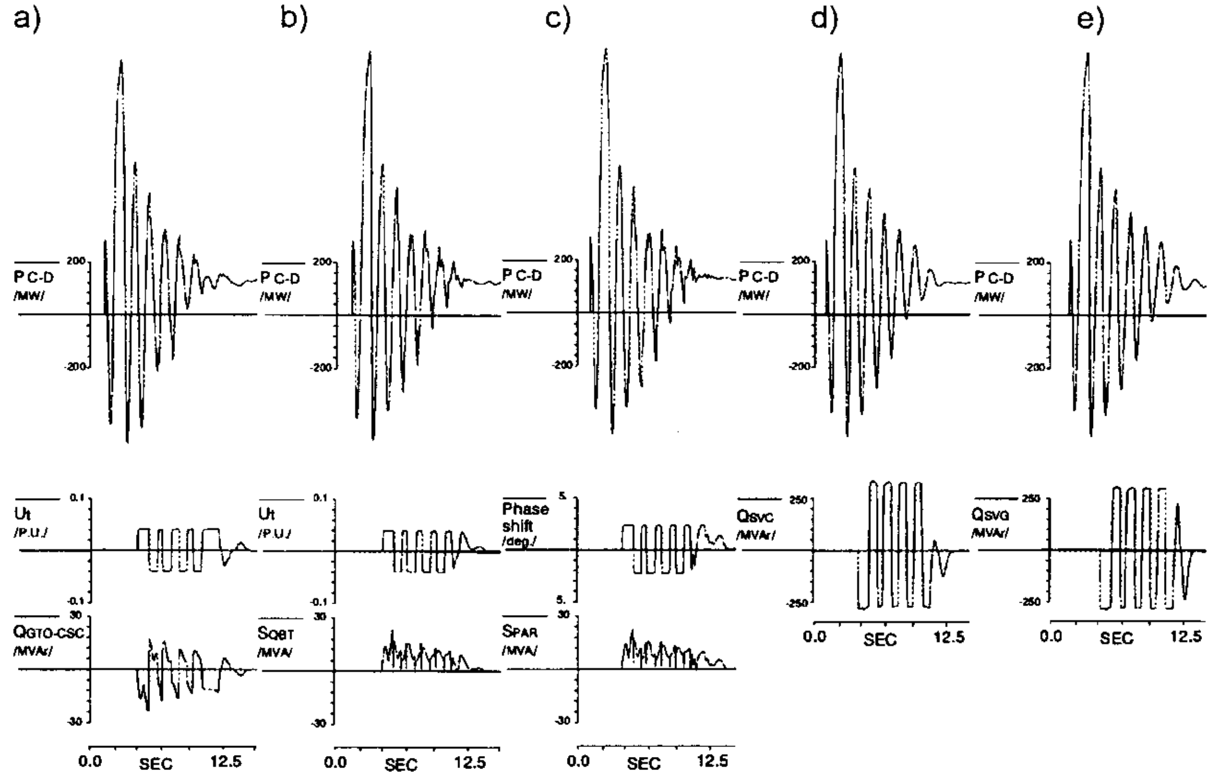


Figure: 4.20 Power oscillation damping
a) GTO-CSC b) QBT c) PAR d) SVC e)SVG

As shown in Fig. 4.18 the GTO-CSC, QBT and PAR are located near the node C, while the SVC and SVG devices are connected to the bus in the middle of the connection between C and D. While the location of the GTO-CSC, QBT and PAR in the connection between C and D has minor impact, the correct location of the SVC and SVG is essential for power oscillation damping effectiveness. For controllable parallel compensation the most favourable location between C and D is near to the middle of the connection. Connected to node C, the SVC and SVG do not contribute to power oscillation damping.

4.5.3 Synthesis

The ratings of the different FACTS devices used in the study which improve meshed system damping are presented in the table 4.3. In the cases of the GTO-CSC, QBT and PAR the peak values and the approximate average powers during the bang-bang action are also presented (Fig. 4.20).

It is evident from the results that a QBT and a PAR will have nearly identical effects on power oscillation damping. The reason for is that the impact of a QBT and PAR on system transmission characteristics only differs if the stiff voltage node is in the vicinity of the device location (as shown in sec. 3.4). If the PAR or QBT is "within" the electric network the impact of these two devices on power transmission characteristics becomes similar [24]. Similar conclusions can be made when an SVC and SVG are compared. They have also almost identical impact on power oscillation damping. The reason for that is the fact, that SVC and SVG terminal voltage is in both cases near the rated value.

GTO-CSC			QBT			PAR			SVC	SVG
U_T /P.U./	power /MVA/		U_T /P.U./	power /MVA/		phase shift	power /MVA/		rating /MVAr/	rating /MVAr/
	peak	avg.		peak	avg.		peak	avg.		
0.04	23	10	0.04	23	10	2.3°	23	10	280.	280.

Table 4.3: Comparison of the FACTS devices efficiency

From the results it also appears that the GTO-CSC effect on power oscillation damping is very similar to the effect of phase shifting transformers (QBT and PAR) although they implement different physical principles to achieve dynamic real power flow control (control of line impedance in the case of GTO-CSC and control of transmission angle in the case of phase shifting transformers). This conclusion is not surprising when the results of sec. 3.5 are kept in mind. Fig. 3.27 of sec. 3.5 presents the impact of various FACTS devices on the real and reactive power flow on the loop-formed system. Thus on the system used in this study the oscillating power is mainly the loop power flowing along "A-B-C-D" loop, and the conclusions of sec 3.5.1 are in general valid also here. When comparing Fig. 3.27a and 3.27b of sec. 3.5.1, it is evident, that for a small ratio U_T/U the impact of GTO-CSC and phase shifting transformer on real power flow is nearly identical. This explains the similar effect of GTO-CSC and phase shifting transformers on power oscillation damping.

When the effectiveness of GTO-CSC, QBT and PAR's are compared with SVC and SVG effectiveness it is evident, that the necessary difference in device rating is about one order of magnitude. A similar result is presented in sec. 3.1.3.

4.6 Power Oscillation Damping in Transmission System

4.6.1 System Configuration

The system configuration examined is shown in Fig. 4.21. It consists of three subsystems interconnected by transmission lines. It represents a configuration which may exist in various countries.

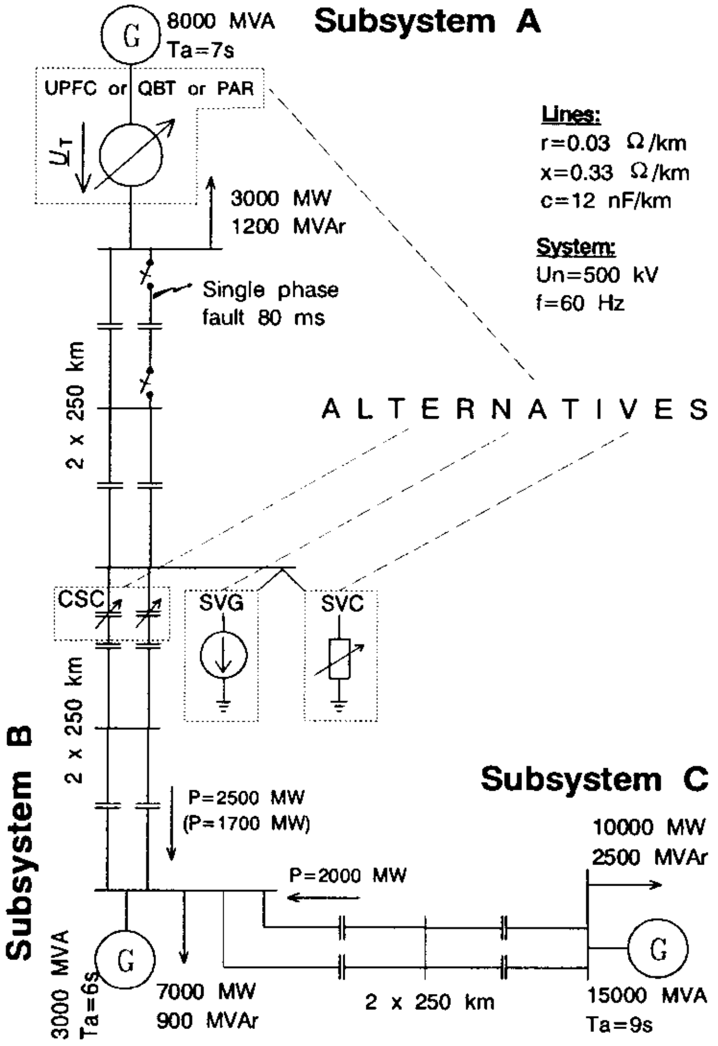


Figure 4.21: System configuration

The generation capabilities of individual subsystems of this system can be seen in Fig. 4.21. Powers from subsystems A and C are transmitted to the generation deficient subsystem B via two double transmission lines. The investigation is based on the heavy-load case. A spinning reserve of the systems A and B to cover outages amounts to 10% and of the system C to 5% of generation capability. The subsystems are represented by equivalent generators and loads, which has been determined from a more complex configuration by parameter identifying procedures. For each subsystem it was assumed that part of the generators are equipped with Power System Stabilizer (PSS).

The lines are divided into 250 km sections. During normal operation 70% series compensation in all line sections and 50% parallel compensation by shunt reactors is assumed and modelled. To assure the appropriate voltage conditions and reactive power flow during normal operation part of the shunt compensation is disconnected. In steady-state conditions the operating voltage in the whole system is well inside the normal limits.

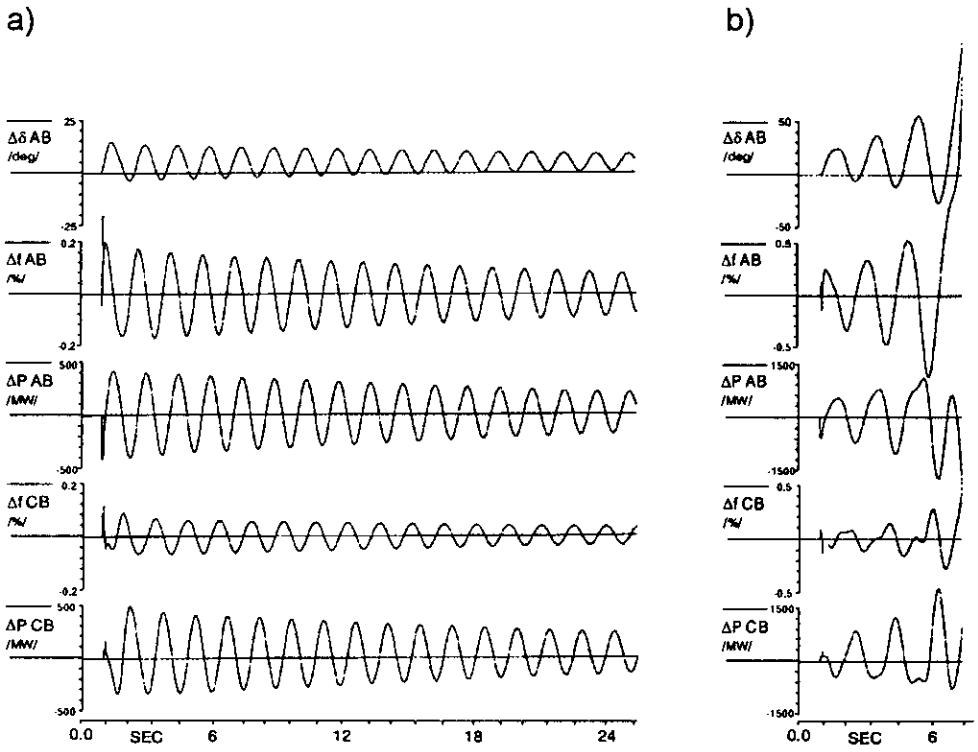


Figure 4.22 System performance without FACTS devices
$\Delta\delta$ - rotor angle difference,
Δf - frequency difference,
ΔP - active power oscillations,
AB and CB - quantities related to transmission between subsystems A-B and C-B respectively.
Transmitted power: **a)**1700 MW **b)**2500 MW

The active power component of loads in the subsystems was considered to vary with the power of 1.1 and the reactive power component with the power of 2 of the voltage

The FACTS devices are in the system positioned as shown in the Fig. 4.21. The best location for the parallel compensation is in the middle of the transmission system between A and B.

The location of the CSC and the phase angle regulator (PAR) between A and B practically is not important, whilst the best location of (QBT) and of UPFC is near to system A.

4.6.2 Simulation

Modelling and a digital simulation are carried out using the stability mode of the NETOMAC program system. The generators, including excitation systems and PSS, were simulated in detail. The loads were simulated by voltage dependent impedances. The FACTS devices were modelled as controllable impedances, current sources and voltage sources including their combinations (c.f. sec. 3.3 and 3.5.2)[27].

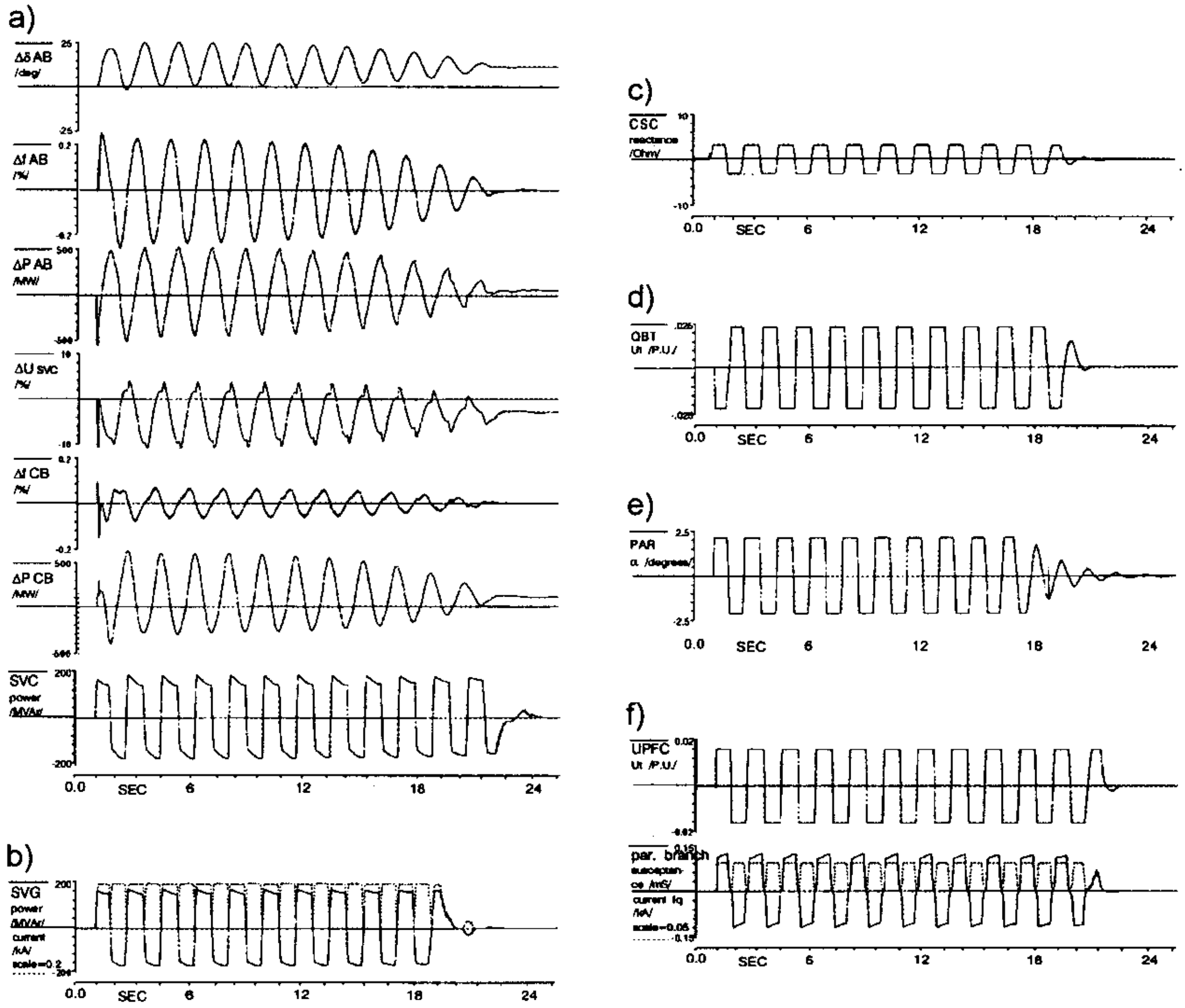


Figure 4.23: System performance with FACTS devices included
a)SVC b)SVG c)CSC
d)QBT e)PAR f)UPFC

The disturbance in the system is represented by an 80 ms single phase fault followed by the line disconnection as shown in the Fig. 4.21. Without additional measures the maximum transmission capability is 1700 MW. In this case the system is slightly positively damped. If the power transfer is increased over this level the system damping becomes negative. The aim of the study was to determine the necessary rating of FACTS devices (minimum limits) to assure positive damping if the transmission power is increased to 2500 MW. If the ratings of the FACTS devices are only slightly lower, system damping is not positive.

The system performance when the FACTS devices are not active is presented in Fig. 4.22. As shown in the Figure 4.22b damping of the system, when 2500 MW power is transmitted is negative and the system loses synchronism in about 6 seconds after three power swings.

In the studied system the power oscillations between A and B are critical and therefore the object was to damp this mode of oscillations by FACTS devices. The rotor angle difference between the subsystems A and B was used as the FACTS controller input variable.

The comparison of different tools in order to reach the objective represents the first phase in feasibility studies. In this case the objective was to achieve positive damping of transmission system by different FACTS devices. In order to achieve relevant results all devices should be explored to the optimum. It is evident from the literature how to control them (with exception of UPFC) to achieve effective system damping. To achieve efficient UPFC behaviour during the dynamic phenomena, the most effective combination of the three controllable parameters (the magnitude and the phase of injected series branch voltage as well as parallel branch reactive current - [28]) has been determined using on-line calculation of the simplified model incorporated in the UPFC control [28]. In this way is it possible to evaluate UPFC efficiency and to compare it with other devices.

The oscillogram of some characteristic system quantities when an SVC is included as a damping device are shown in Fig. 4.23a. If other FACTS devices are included in the system these quantities are similar so only the output of the FACTS device is plotted.

As shown in Fig. 4.23. the series and parallel compensation have the same ratings in the inductive and in the capacitive operating area. The shift of the operating area into one direction (inductive or capacitive) - difference between limits remaining unchanged - has only a minor impact on the power oscillation damping effect. In the case of phase shifting devices (PAR, QBT) the limit of the injected voltage magnitudes in both directions (phase shift in positive or negative direction) are equal. In the case of the UPFC it has been assumed, it has ideal operating characteristic in the form of the area limited by the circuit with the radius defined by the UPFC rating. This operating area extends if the UPFC terminal voltage is controlled by the series branch reactive power control [28].

For the purpose of the comparison of the controlled power, the ratings of the phase shifting transformers and the UPFC were calculated from pre-fault current and the maximal injected voltage which assures positive damping of the system power oscillations (limit value). During the transients following the system disturbance the device throughput power may be considerably higher. The same is valid also in the case of a CSC.

4.6.3 Synthesis

The ratings of the different FACTS devices which assure positive system damping when the power flow between subsystems A and B is 2500 MW are summarised in table 4.4. The SVG overload capability and the possibility of the disconnection of the line with an CSC (therefore its rating must be higher) were not taken into consideration. As anticipated the most effective device is a UPFC as it represents a combination of parallel and series compensation as well as phase shifting devices. The optimal combination of them (optimal UPFC parameters) is the most efficient solution.

CSC		SVC	SVG		QBT		PAR		UPFC	
% comp.	rating /MVA/	rating /MVA/	current /kA/	rating /MVA/	U_T /P.U./	rating /MVA/	phase shift	rating /MVA/	U_T /P.U./	rating /MVA/
5.17	67	170	0.187	162	0.022	66	2.05°	107	.0158	47

Table 4.4: Comparison of the FACTS devices efficiency

5. Conclusions

- FACTS elements can be divided into shunt (e.g. SVC, SVG) and series elements (e.g. CSC, GTO-CSC, PST, QBT). The UPFC and IPC can however, combine the abilities of both types. The impact of series elements on the control of active power flow is much stronger compared to the shunt elements. The series elements are also more effective in power oscillation damping and transient stability improvement which can be achieved by modulation of active power. Shunt elements are used primarily for voltage control and can have power oscillation damping control added.

- Table 5.1 sumarises the impact of different FACTS elements on the different problems that arise in power systems. The table considers only the technical abilities of the equipment. The UPFC offers the best performance for all discussed system problems. However, meeting requirements for all of these problems may lead to very high rating for the device.

- The impact of FACTS elements in long distance transmission systems and in interconnected meshed systems is different. In long distance transmission CSC offer advantages comparing effectiveness related to the rating and complexity. The PST may offer similar damping of power oscillation but contribute less on transient stability improvement UPFC has a stronger impact on transient stability and oscillation damping, however, it has high complexity.

- In the meshed systems active load flow can be effectively controlled by PAR, QBT and IPC devices. The UPFC can however in addition control also reactive power flow. A CSC is less suitable for such application.

- The impact of series FACTS elements in the system is less sensitive to the device location than shunt elements. This is valid for long distance and meshed systems. For shunt elements, however, the optimum location is very important for their effectiveness.

- The effectiveness of FACTS elements depends strongly on the system configuration and no general conclusions can be made. The final decision can be taken only following detailed studies that take into account various FACTS elements.

- Comparison of the ratings required for the various FACTS elements with comparable effectiveness has been evaluated and reported for some cases. However, cost efficiency can not be fully analysed at the present stage of device development.

	SVC	SVG	CSC	GTO-CSC[1)	PST	UPFC	IPC 2)
Voltage control	***	***	*	*	*	***	
Load flow control (meshed system)	-	-	*	**	***	***	***
Transient stability (transmission system)	*	*	***	***	**	***	
Oscillation damping (transmission system)	*	*	***	***	**	***	
Oscillation damping (meshed system)	*	*	*	**	**	***	

-	low or no influence
*	small influence
**	medium influence
***	strong influence
1)	thyristor controlled
2)	mechanically switched

Table: 5.1 Impact of FACTS elements on system problems

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Appendix:

Glossary

The IEEE FACTS working group has a task force assigned to developing a set of terms which will provide a common basis for discussing the various concepts described in this document. This task is nearing completion, and will conclude with a paper and a submission to the IEEE dictionary of a finally agreed to set of terms. The current set of terms is included in this section, but may change somewhat prior to completion of the task force assignment.

Flexibility of Electric Power Transmission
The ability to accommodate changes in the electric transmission system or operating conditions while maintaining sufficient steady state and transient margins.

FACTS
Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability.

FACTS Controller
A power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters.

Battery Energy Storage System (BESS)
A chemical-based energy storage system using shunt connected, switching converters to supply or absorb energy to/from an ac system which can be adjusted rapidly.

Interphase Power Controller (IPC)
A series-connected power controller consisting, in each phase, of inductive and capacitive branches subjected to separately phase shifted voltages. The active and reactive power be set independently by adjusting the phase shifts and/or the branch impedances, using mechanical or electronic switches. In particular case where the inductive and capacitive impedances form a conjugate pair, each terminal of the IPC is a passive current source dependent on the voltage at other terminal.

Static Synchronous Compensator (SSC or StatCom)
A static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independently of the ac system voltage.

Static Synchronous Condenser (STATCON)
This term is deprecated in favour of the Static Synchronous Compensator (SSC or SatCom).

Static Synchronous Generator (SSG)
A static, self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multi-phase output voltages, which may be coupled to an ac power system for the purpose of exchanging independently controllable real and reactive power.

Static Synchronous Series Compensator (SSSC or S^3C)
A static, synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. The S^3C may include transiently rated energy storage or energy absorbing device to enhance the dynamic behavior of the power system by additional temporary real power compensation to increase or decrease momentarily the overall real (resistive) voltage drop across the line.

Static Var Compensator (SVC)
A shunt-connected static var generator/absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).

Static Var Generator or Absorber (SVG)
A static electrical device, equipment, or system that is capable of drawing controlled capacitive and/or inductive current from an electrical power system and thereby generating or absorbing reactive power. Generally considered to consist of shunt-connected, thyristor-controlled reactor(s) and/or thyristor-switched capacitors.

Static Var System (SVS)
A combination of different static and mechanically-switched var compensators whose outputs are co-ordinated.

Super Conducting Magnetic Energy Storage (SMESS)
A superconducting electromagnetic based energy storage system using shunt-connected switching converters to rapidly exchange energy with an ac system.

Thyristor Controlled Braking Resistor (TCBR)
A shunt-connected, thyristor-switched resistor, which is controlled to aid stabilisation of a power system or to minimise power fluctions on a generating unit.

Thyristor Controlled Phase Shifting Transformer (TCPST)
A phase-shifting transformer, adjusted by thyristor switches to provide a rapidly varying phase angle.

Thyristor Controlled Reactor (TCR)
A shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve.

Thyristor Controlled Series Capacitor (TCSC)
A capacitive reactance compensator which consists of series capacitor banks shunted by thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance.

Thyristor Controlled Series Compensation
An impedance compensator which is applied in series on an ac transmission system to provide smooth control of series reactance.

Thyristor Controlled Series Reactor (TCSR)
An inductive reactance compensator which consists of series reactor shunted by thyristor controlled reactor in order to provide a smoothly variable series inductive reactance.

Thyristor Controlled Voltage Limiter (TCVL)
A thyristor-switched metal-oxide varistor (MOV) to limit the voltage across the terminals during transient conditions.

Thyristor Switched Capacitor (TSC)
A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a step-wise manner by full- or zero-conduction operation of the thyristor valve.

Thyristor Switched Reactor (TSR)
A shunt-connected, thyristor-switched inductor whose effective reactance is varied in a step-wise manner by full- or zero-conduction operation of the thyristor valve.

Thyristor Switched Series Capacitor (TSSC)
A capacitive reactance compensator which consists of series capacitor banks shunted by a thyristor switched reactor to provide a step-wise control of series capacitive reactance.

Thyristor Switched Series Compensation
An impedance compensator which is applied in series on an ac transmission system to provide a step-wise control of series reactance.

Thyristor Switched Series Reactor (TSSR)
An inductive reactance compensator which consists of series reactor shunted by thyristor switched reactor in order to provide a step-wise control of series inductive reactance.

Unified Power Flow Controller (UPFC)
A combination of a static synchronous compensator (StatCom) and a static synchronous series compensator (S^3C) which are coupled via a common dc link, to allow bi-directional flow of real power between the series output terminals of the S^3C and shunt output terminals of the StatCom, and are controlled to provide concurrent real and reactive series compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and

angle or, alternatively, the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation.

Var Compensating System (VCS)

A combination of different static and rotating var compensators whose outputs are co-ordinated.

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