Unit: 06

TCVR, TCPAR and Combined Compensators (UPFC and IPFC)

Unit Content:

Objective of voltage and phase angle regulators, approaches to TCVR and TCPAR, Switching converter based Voltage and Phase angle Regulators, Basic operating principles UPFC, control structure of UPFC, Basic operating principles and characteristics of IPFC, Control structure and applications of IPFC.

6.1 Introduction:

The transmitted real power, P, and reactive line power, Q, are a function of the transmission line impedance, the magnitude of the sending- and receiving- end voltages, and the phase angle between these voltages. Already discussed that control of transmitted power by series reactive compensation which can be a highly effective means to control power flow in the line as well as improving the dynamic behavior of the power system. However, whereas series reactive compensation is generally highly effective for power flow control, but it can impractical, or economically not viable for some application.

Problems involve the control of real and reactive loop flows in a meshed network. The solution to these types of problems usually requires the control of the effective angle**.** Apart from 'steady-state voltage and power flow control, the role of modern voltage and phase angle regulators with fast electronic control can also be extended to handle dynamic system events. As compared to reactive compensators, voltage and phase angle regulators bring a new element to the control of dynamic events, the capability to exchange real power.

6.2 Voltage and Phase Angle Regulation:

The basic concept of voltage and phase angle regulation is the addition of an appropriate in-phase or a quadrature component to the prevailing terminal voltage in order to change (increase or decrease) its magnitude or angle to the value specified (or desired). Thus, voltage regulation could, theoretically, be achieved by a synchronous, in-phase voltage source with controllable amplitude, $\pm \Delta V$ in series with the ac system. An adjustable voltage is provided by means of a tap changer from a three-phase (auto) transformer for the primary of a series insertion transformer which injects it to achieve the required voltage regulation.

From the arrangement shown in fig. (1) Below, it is evident that injected voltages $\pm \Delta V_a$, $\pm \Delta V_b$ and $\pm \Delta V_c$, are in phase with the line to neutral voltages V_a, V_b, and V_c respectively.

In a similar manner, the arrangement can be used for phase angle control simply i.e. the injected voltage, ΔV, to have a phase of $\pm 90°$ relative to the system voltage V, as shown in fig. (2) below.

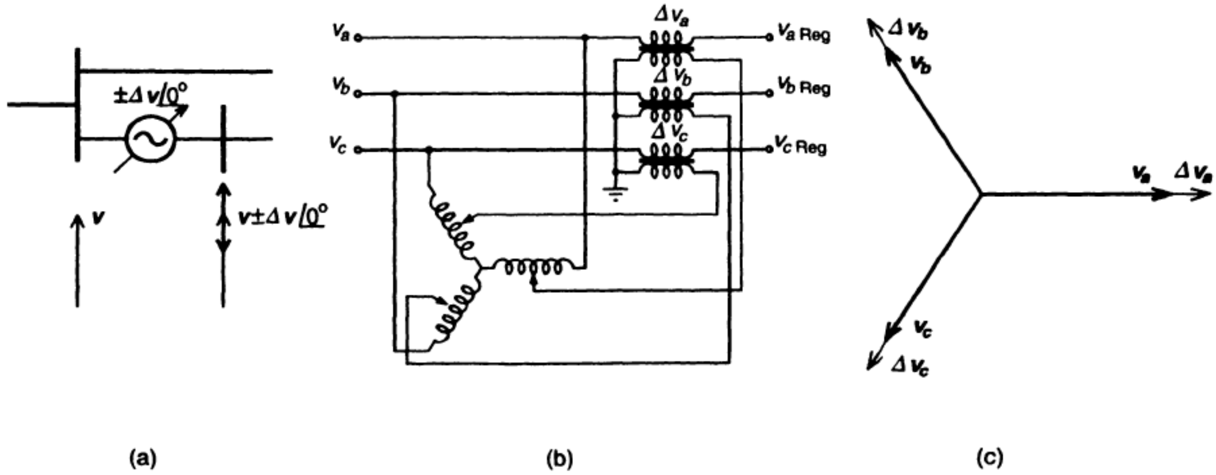


Fig. (1): Concept and basic implementation of a Voltage Regulator.

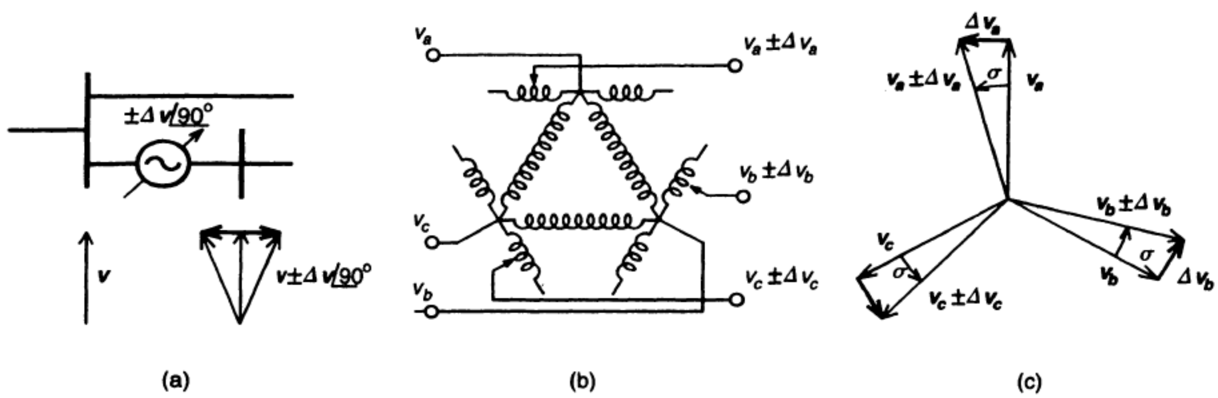


Fig. (2): Concept and basic implementation of a Phase Angle Regulator.

For relatively small angular adjustments, the resultant angular change is approximately proportional to the injected voltage, while the voltage magnitude remains almost constant. For large angular adjustments, the magnitude of the system voltage will appreciably increase and, for this reason, is often referred to as a quadrature booster transformer (QBT). The QBT arrangement has typically been used in conventional phase shifting applications.

6.3 Objectives of Voltage and Phase Angle Regulation:

i. The basic concept of voltage and phase angle regulation is the addition of an appropriate in-phase or a quadrature component to the prevailing terminal (bus) voltage in order to change (increase or decrease) its magnitude or angle to the value specified (or desired).

ii. when power between two buses is transmitted over parallel lines of different electrical length or when two buses are inserted whose prevailing angle difference is insufficient to establish the desired power flow. In these cases a Phase Angle Regulator (PAR) is frequently applied.

iii. Generally, the distribution of real power flow over interconnections forming loop circuits can be controlled by Phase Angle Regulators. The flow of reactive power can be controlled by Voltage Regulators.

iv. Both voltage and angle regulators can clearly provide major benefits for multiline and meshed systems: the full utilization of transmission assets (decrease of reactive power flow, control and balance of real power flow) and reduction of overall system losses through the elimination of circulating loop currents.

v. The capability of the Phase Angle Regulator to maintain the maximum effective transmission angle can also be utilized effectively to increase the transient stability limit.

vi. Transmission angle control can also be applied to damp power oscillations.

6.4 Approaches to Thyristor-Controlled Voltage and Phase Angle Regulators (TCVRSs AND TCPARs):

The thyristor controller used in (voltage and angle) regulators will be referred to as the thyristor tap changer. Thyristor tap changers may be configured to provide continuous or discrete level control. Continuous control is based on delay angle control, similar to that introduced for the TCR. Delay angle control, as seen, inevitably generates harmonics.

To achieve little or no harmonic generation, thyristor tap changer configurations must provide discrete level control.

6.4.1 Continuously Controllable Thyristor Tap Changers:

There are a number of possible thyristor tap changer configurations which can give continuous control. The basic power circuit scheme of a thyristor tap changer considered here is shown in Figure 4(i). This arrangement can give continuous voltage magnitude control by initiating the onset of thyristor valve conduction.

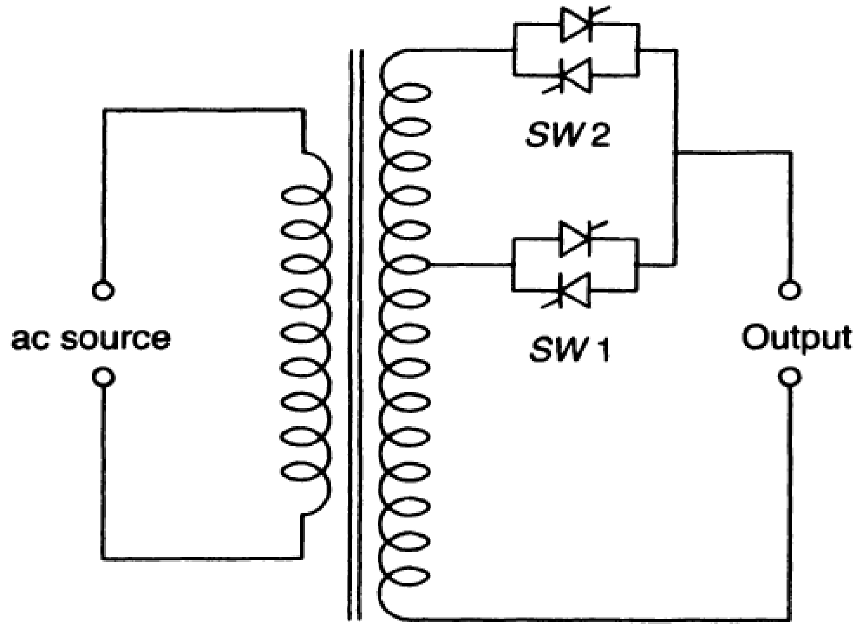


Fig. 3(i): Basic thyristor tap-changer circuit configuration for continuous (delay angle) control of the output voltage

The two thyristor valves employed need only be rated according to maximum percentage voltage regulation required. However, as indicated earlier, such schemes giving continuous control suffer from two drawbacks:

i) They create harmonics of the supply frequency in their terminal voltage

ii) Implementation of their control for all load power factors is relatively complex.

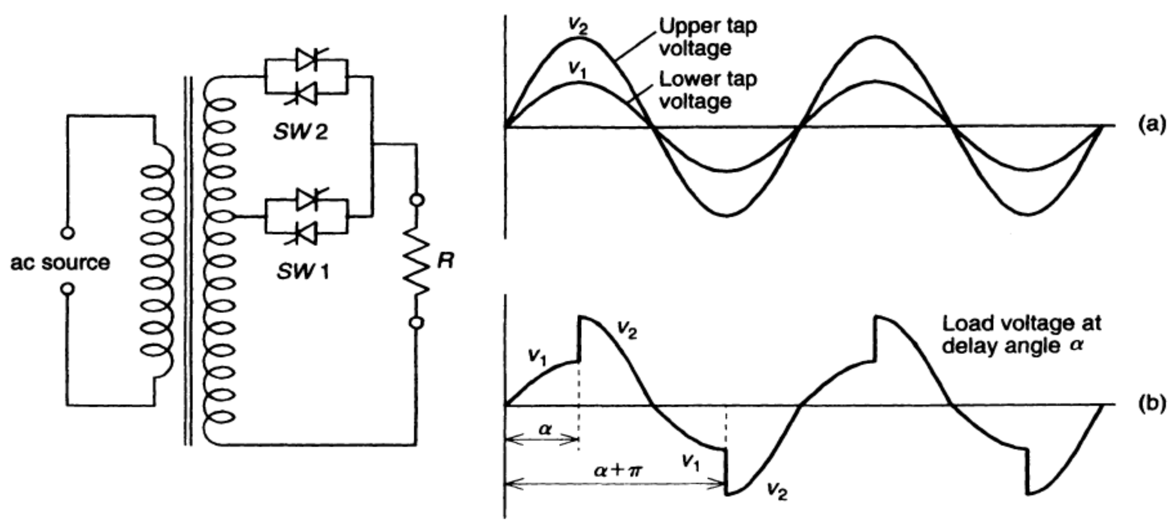


Fig. 3(ii): Output voltage waveform of the delay angle controlled thyristor tap changer supplying a resistive load.

Consider Figure 3(ii) and assume that a resistive load is connected to the output terminals of the thyristor tap changer. This load of course could be the line current in phase with the terminal voltage. The two voltages obtainable at the upper and lower taps, V_1 and V_2, respectively, are shown in Fig. 4(ii) (a). The gating of the thyristor valves is controlled by the delay angle α with respect to the voltage zero crossing of these voltages. For example, Fig. 3(ii) (b) shows that at α = 0, at which, in the present case of a resistive load, the current crosses zero and thus the previously conducting valve turns off, valve SW_1 turns on to switch the load to the lower tap. At $\alpha = \alpha_1$, valve SW_2 is gated on, which commutates the current from the conducting thyristor valve SW_1 by forcing a negative anode to cathode voltage across it and connecting the output to the upper tap with voltage V_2. Valve SW_2 continues conducting until the next current zero is reached (in the present case, the next current zero coincides with the voltage zero crossing.

6.4.2 Thyristor Tap Changers with Discrete Level Control:

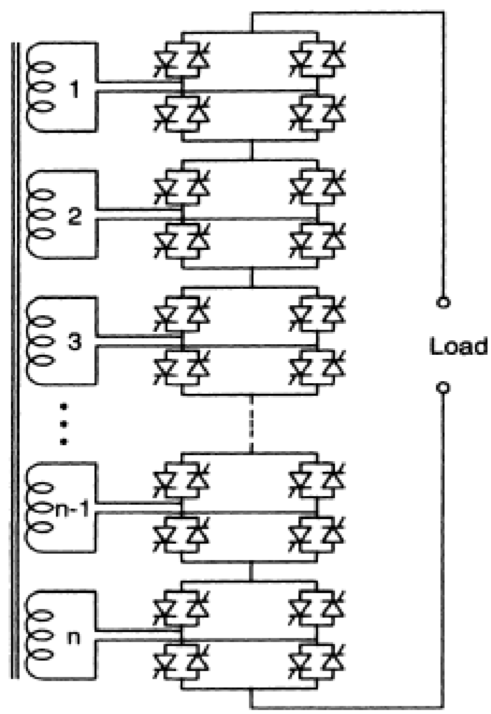


Fig.4 (a): Thyristor tap changer using equal winding sections for discrete level voltage control.

The problems associated with a continuously controllable thyristor tap changer can be avoided with the application of discrete level voltage control employed in conventional electromechanical tap changers. With discrete level control the tap-changing function can be achieved without introducing harmonic distortion or undesirable phase shifts and without the control complexities associated with continuous control. The choice of power circuit is decided by performance requirements and cost.

A conceptually simple tap-changing configuration is shown in Fig. (a). In this scheme each winding section is bridged by four bi-directional thyristor valves, and thus may be inserted in the transmission line, giving 0 to ± V volts availability in V/n steps. If 16 equal sections are used to give 33 steps capability over V volts with current rating I, then the total required thyristor valve rating is (V/16 X 64)I = 4 VI. It is also important to recognize that the thyristor tap changer, in contrast to the previously considered shunt and reactive compensators, can neither generate nor absorb reactive power.

The reactive power supplied to or absorbed from a line when it injects in phase or quadrature voltage must be absorbed by or supplied to it by the ac system. For this reason, both the series insertion and shunt regulating transformers must be fully rated for the total *VI* product. The circuit configuration shown in Fig.4 (a) also has some practical disadvantages. The winding must be broken into n equal sections for 2n + 1 total number of required steps, and 4n thyristor valves are used. A major problem with this is the difficulty of producing a transformer with n small and isolated winding sections, with 2n leads coming from the winding structure. Another disadvantage of this configuration is that at lower system voltages, i.e., smaller controlled voltage V, the voltage per winding section becomes much lower than the minimum economic voltage application point of power thyristors currently available.

6.5 Switching Converter-based Voltage and Phase Angle Regulators:

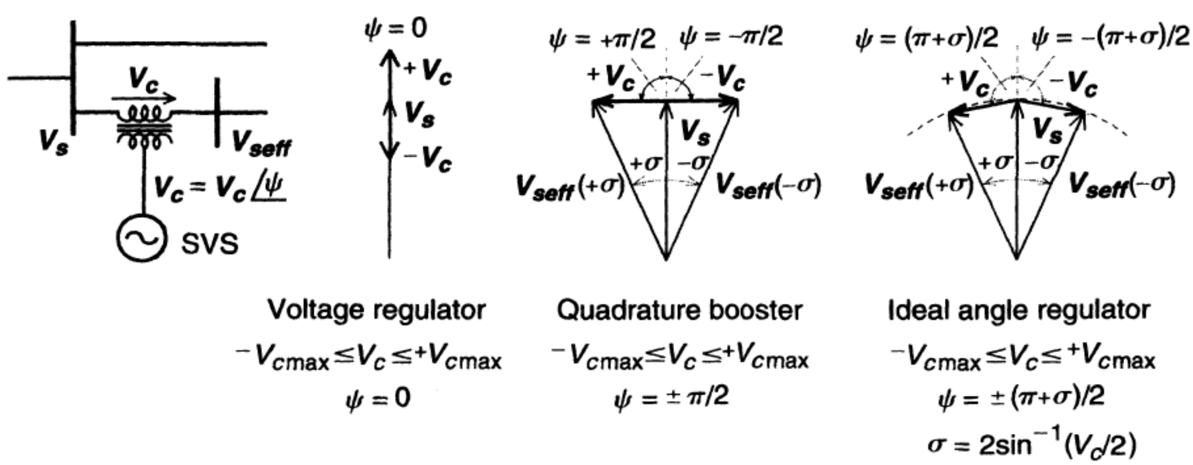
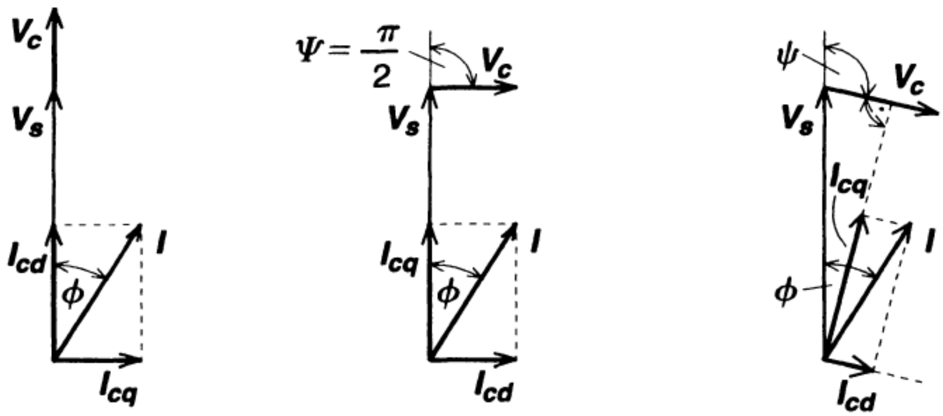


Fig.5 (a) Synchronous Voltage Source used for voltage regulation, "quadrature boosting" and phase angle regulation.

The voltage-sourced converter exhibits the characteristics of a theoretical SVS: it can produce a substantially sinusoidal output voltage at the fundamental frequency with controllable amplitude and phase angle and can self-sufficiently generate reactive power for and exchange real (active) power with the ac system. Synchronous voltage source is applied as a series reactive compensator to inject a controllable voltage in quadrature with the line current.

It is shown that such a compensator, when appropriately supplied with dc power, then injecting a voltage component that is in phase with the line current. Therefore it should be possible that a converter-based SVS with controllable amplitude V, and phase angle ψ can be used for voltage and phase angle regulation by setting ψ = 0 and ψ = ± π/2 (quadrature booster) or ψ = ± (π + σ)/2, where σ is the desired angular phase shift produced by the injection of voltage phasor.



$$P_c = V_c I_{cd} = V_c I \cos\phi \qquad P_c = V_c I_{cd} = V_c I \sin\phi \qquad P_c = V_c I_{cd} = V_c I \cos(\psi - \phi)$$

$$Q_c = V_c I_{cq} = V_c I \sin\phi \qquad Q_c = V_c I_{cq} = V_c I \cos\phi \qquad Q_c = V_c I_{cq} = V_c I \sin(\psi - \phi)$$

Fig.5 (b) Phasor diagrams showing the real and reactive power the Synchronous Voltage Source exchanges when operated as a Voltage Regulator, Quadrature Booster, and Phase Angle Regulator.

The synchronous voltage source used as a voltage or angle regulator will generally exchange both real and reactive power as shown in Fig. (b). The in-phase and quadrature components of an assumed load current with respect to the voltage inserted for voltage regulation, quadrature boosting and ideal phase angle control are shown together with the corresponding expressions for the real and reactive power the SVS exchanged.

Combined Compensators (UPFC and IPFC)

Introduction

The objective of this chapter is to investigate the application potential of multifunctional FACTS Controllers based on the back-to-back voltage-sourced converter arrangement. This arrangement offers two basic possibilities. In the first Controller one converter of the back-to-back arrangement is in series and the other is in shunt with the transmission line. This arrangement in transmission applications is, for reasons explained later, generally referred to as the Unified Power Flow Controller (UPFC). This UPFC identification is quite universal for this arrangement, although the UPFC, like the STATCOM and SSSC, could be implemented by a variety of different switching converters. In the second Controller both converters of the back-to-back arrangement are connected in series with, usually, a different line. This arrangement is referred to as the Interline Power Flow Controller (IPFC).

6.6: Unified Power Flow Controller (UPFC)

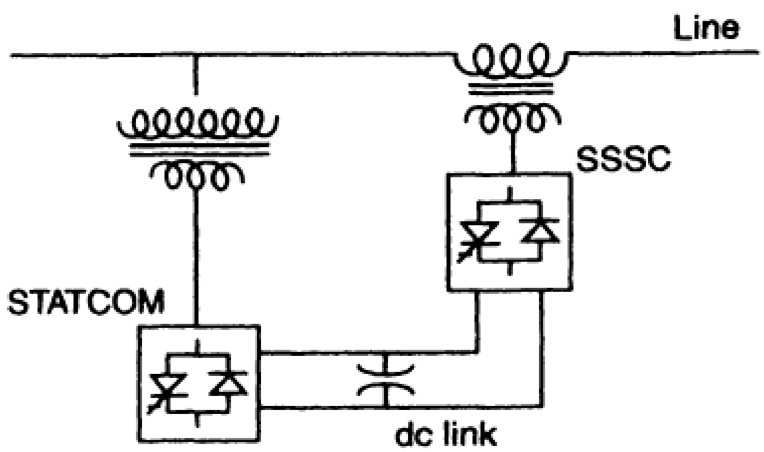


Figure 6.1: Unified Power Flow Controller (UPFC)

The Unified Power Flow Controller (UPFC) concept was proposed by Gyugyi in 1991. The UPFC was devised for the real-time control and dynamic compensation of ac transmission systems, providing multifunctional flexibility required to solve many of the problems facing the power delivery industry. Within the framework of traditional power transmission concepts, the UPFC is able to control, simultaneously or selectively, all the parameters affecting power flow in the transmission line (i.e., voltage, impedance, and phase angle), and this unique capability is signified by the adjective "unified" in its name. Alternatively, it can independently control both the real and .reactive power flow in the line.

A combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via a common dc link, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent real and reactive series line 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.

6.6.1: Basic Operating Principles of UPFC

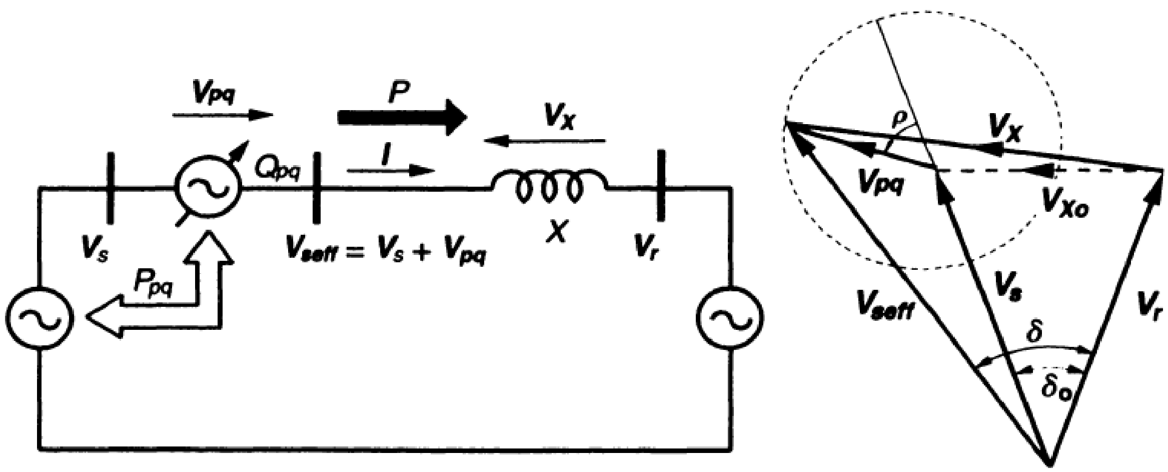


Figure 6.2: Conceptual representation of the UPFC in a two-machine power system

From the conceptual viewpoint, the UPFC is a generalized synchronous voltage source (SVS), represented at the fundamental (power system) frequency by voltage phasor Vpq with controllable magnitude Vpq ($0 \leq Vpq \leq Vpqmax$) and angle ρ ($0 \leq \rho \leq 2\pi$), in series with the transmission line, as illustrated for the usual elementary two machine system (or for two independent systems with a transmission link intertie) in Figure 5.2. In this functionally unrestricted operation, which clearly includes voltage and angle regulation, the SVS generally exchanges both reactive and real power with the transmission system. Since, as established previously, an SVS is able to generate only the reactive power exchanged, the real power must be supplied to it, or absorbed from it, by a suitable power supply or sink. In the UPFC arrangement the real power exchanged is provided by one of the end buses (e.g., the sending-end bus), as indicated in Figure 6.2.

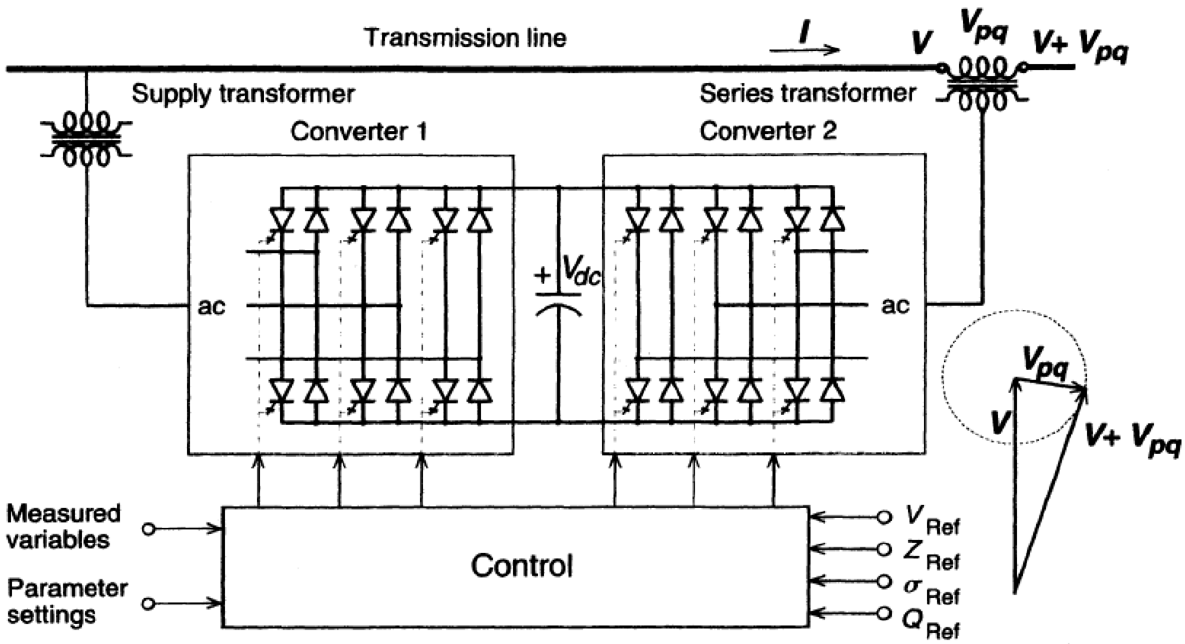


Figure 6.3: Implementation of the UPFC by two back-to-back voltage-sourced converters.

In the presently used practical implementation, the UPFC consists of two voltage sourced converters, as illustrated in Figure 5.3. These back-to-back converters, labeled "Converter 1" and "Converter 2" in the figure, are operated from a common dc link provided by a dc storage capacitor. As indicated before, this arrangement functions as an ideal ac-to-ac power converter in which the real power can freely flow in either direction between the ac terminals of the two converters, and each converter can independently generate (or absorb) reactive power at its own ac output terminal.

Converter 2 provides the main function of the UPFC by injecting a voltage *Vpq* with controllable magnitude *Vpq* and phase angle ρ in series with the line via an insertion transformer. This injected voltage acts essentially as a synchronous ac voltage source. The transmission line current flows through this voltage source resulting in reactive and real power exchange between it and the ac system. The reactive power exchanged at the ac terminal (i.e., at the terminal of the series insertion transformer) is generated internally by the converter. The real power exchanged at the ac terminal is converted into dc power which appears at the dc link as a positive or negative real power demand.

The basic function of Converter 1 is to supply or absorb the real power demanded by Converter 2 at the common dc link to support the real power exchange resulting from the series voltage injection. This dc link power demand of Converter 2 is converted back to ac by Converter 1 and coupled to the transmission line bus via a shunt connected transformer. In addition to the real power need of Converter 2, Converter 1 can also generate or absorb controllable reactive power, if it is desired, and thereby provide independent shunt reactive compensation for the line. It is important to note that whereas there is a closed direct path for the real power negotiated by the action of series voltage injection through Converters 1 and 2 back to the line, the corresponding reactive power exchanged is supplied or absorbed locally by Converter 2 and therefore does not have to be transmitted by the line. Thus, Converter 1 can be operated at a unity power factor or be controlled to have a reactive power exchange with the line independent of the reactive power exchanged by Converter 2. Obviously, there can be no reactive power flow through the UPFC dc link.

6.7: Control structure of UPFC:

The superior operating characteristics of the UPFC are due to its unique ability to inject an ac compensating voltage vector with arbitrary magnitude and angle in series with the line upon command, subject only to equipment rating limits. With suitable electronic controls, the UPFC can cause the series-injected voltage vector to vary rapidly and continuously in magnitude and/or angle as desired. Thus, it is not only able to establish an operating point within a wide range of possible P, Q conditions on the line, but also has the inherent capability to transition rapidly from one such achievable operating point to any other.

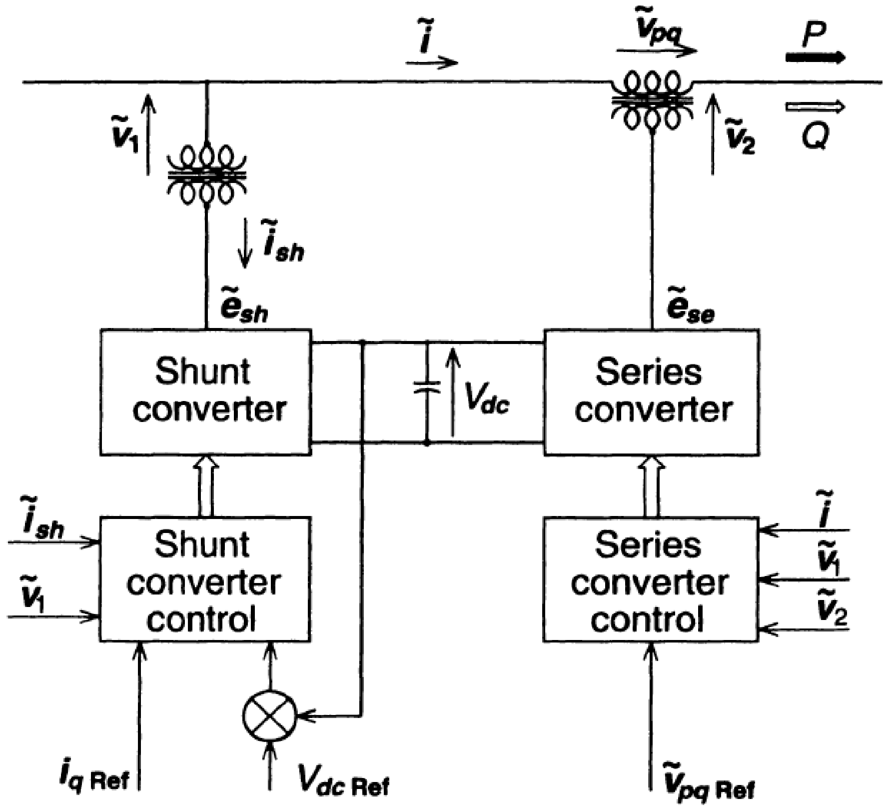


Figure 6.4: Basic UPFC control scheme.

The control of the UPFC is based upon the vector-control approach proposed by Schauder and Mehta for "advanced static var compensators" (i.e., for STATCOMs) in 1991. The term vector, instead of phasor, is used in this section to represent a set of three instantaneous phase variables, voltages, or currents that sum to zero. The symbols v and i are used for voltage and current vectors.

For the purpose of power control it is useful to view these vectors in an orthogonal coordinate system with p and q axes such that the p axis is always coincident with the instantaneous voltage vector v and the q axis is in quadrature with it. In this coordinate system the p-axis current component, i_p , accounts for the instantaneous real power and the q-axis current component, i_q , for the reactive power.

Under balanced steady-state conditions, the p-axis and q-axis components of the voltage and current vector are constant quantities. This characteristic of the described vector represent at in makes it highly suitable for the control of the UPFC by facilitating the decoupled control of the real and reactive current components. The UPFC control system may, in the previously established manner, be divided functionally into internal (or converter) control and functional operation control.

The internal controls operate the two converters so as to produce the commanded series injected voltage and, simultaneously, draw the desired shunt reactive current. The internal controls provide gating signals to the converter valves so that the converter output voltages will properly respond to the internal reference variables, i_{pRef} , i_{qRef} and V_{pqRef}, in accordance with the basic control structure shown in Figure 6.4. As can be observed, the series converter responds directly and independently to the demand for series voltage vector injection. Changes in series voltage vector, 'V_{pq}' can therefore be affected virtually instantaneously.

In contrast, the shunt converter operates under a closed-loop current control structure whereby the shunt real and reactive power components are independently controlled. The shunt reactive power (if this option is used, for example, for terminal voltage control) responds directly to an input demand. However, the shunt real power is dictated by another control loop that acts to maintain a preset voltage level on the dc link, thereby providing the real power supply or sink needed for the support of the series voltage injection.

In other words, the control loop for the shunt real power ensures the required real power balance between the two converters. As mentioned previously, the converters do not (and could not) exchange reactive power through the link. The external or functional operation control defines the functional operating mode of the UPFC and is responsible for generating the internal references, V_{pqRef} and i_{qRef} for the series and shunt compensation to meet the prevailing demands of the transmission system.

The functional operating modes and compensation demands, represented by external (or system) reference inputs, can be set manually (via a computer keyboard) by the operator or dictated by an automatic system optimization control to meet specific operating and contingency requirements.

6.8: Interline Power Flow Controller (IPFC):

The IPFC is a recently introduced Controller and thus has no IEEE definition yet. A possible definition is: The combination of two or more Static Synchronous Series Compensators which are coupled via a common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs, and are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among the lines. The IPFC structure may also include a STATCOM, coupled to the IFFC's common dc link, to provide shunt reactive compensation and supply or absorb the overall real power deficit of the combined SSSCs.

The UPFC concept provides a powerful tool for the cost-effective utilization of individual transmission lines by facilitating the independent control of both the real and reactive power flow, and thus the maximization of real power transfer at minimum losses, in the line. The Interline Power Flow Controller (IPFC), proposed by Gyugyi with Sen and Schauder in 1998, addresses the problem of compensating a number of transmission lines at a given substation. Conventionally, series capacitive compensation (fixed, thyristor-controlled or SSSC-based) is employed to increase the transmittable real power over a given line and also to balance the loading of a normally encountered multiline transmission system. The IPFC scheme, together with independently controllable reactive series compensation of each individual line, provides a capability to directly transfer real power between the compensated lines.

This capability makes it possible to: equalize both real and reactive power flow between the lines; reduce the burden of overloaded lines by real power transfer; compensate against resistive line voltage drops and the corresponding reactive power demand; and increase the effectiveness of the overall compensating system for dynamic disturbances. In other words, the IPFC can potentially provide a highly effective scheme for power transmission management at a multiline substation.

6.8.1: Basic operating principles and characteristics of IPFC:

In its general form the Interline Power Flow Controller employs a number of dc-to-ac converters each providing series compensation for a different line. In other words, the IPFC comprises a number of Static Synchronous Series Compensators. However, within the general concept of the IPFC, the compensating converters are linked together at their dc terminals, as illustrated in Figure 5.9. With this scheme, in addition to providing series reactive compensation, any converter can be controlled to supply real power to the common dc link from its own transmission line. Thus, an overall surplus power can be made available from the under utilized lines which then can be used by other lines for real power compensation. In this way, some of the converters, compensating overloaded lines or lines with a heavy burden of reactive power flow, can be equipped with full two-dimensional, reactive and real power control capability, similar to that offered by the UPFC.

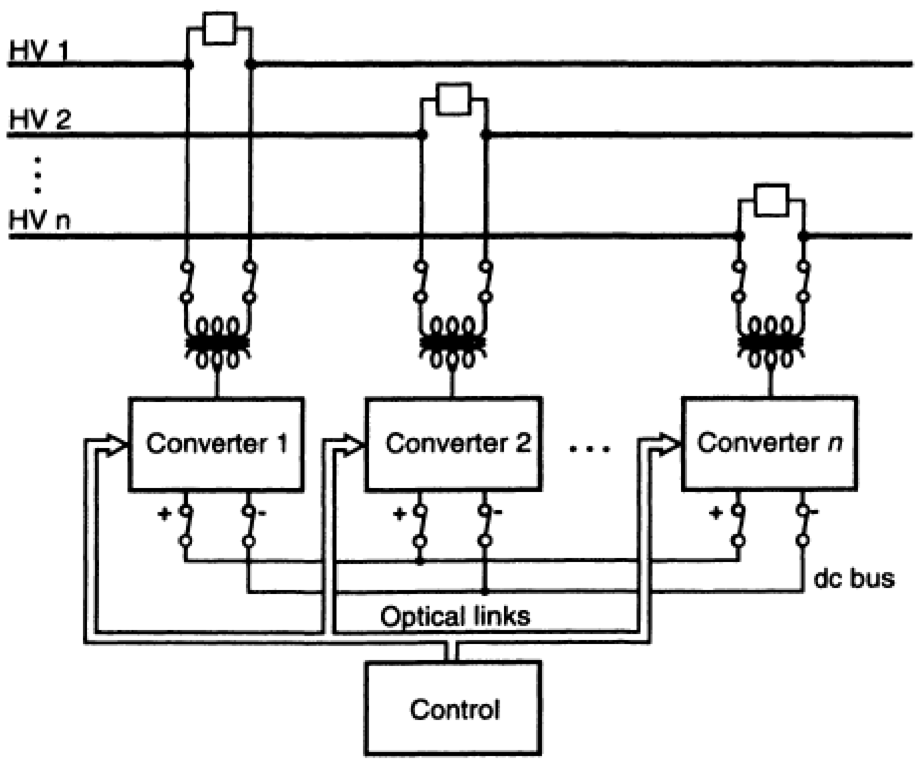


Figure 6.5: Interline Power Flow Controller comprising *n* converters

Evidently, this arrangement mandates the rigorous maintenance of the overall power balance at the common dc terminal by appropriate control action, using the general principle that the under loaded lines are to provide help, in the form of appropriate real power transfer, for the overloaded lines. Consider an elementary IPFC scheme consisting of two back-to-back dc-to-ac converters, each compensating a transmission line by series voltage injection.

6.8.2: Control structure and applications of IPFC:

A possible IPFC control is shown in the form of a block diagram in Figure 5.10. For this structure the assumption of the previous section, stipulating System 1 with IPFC Converter 1 as the "prime" system requiring the independent control of both real and reactive power is, for clarity, retained. This stipulation makes the control of the two converters functionally somewhat different. However, the reader should note that in practice the two converter controls would be identical with control inputs putting either converter in the "prime" or "support" operating role.

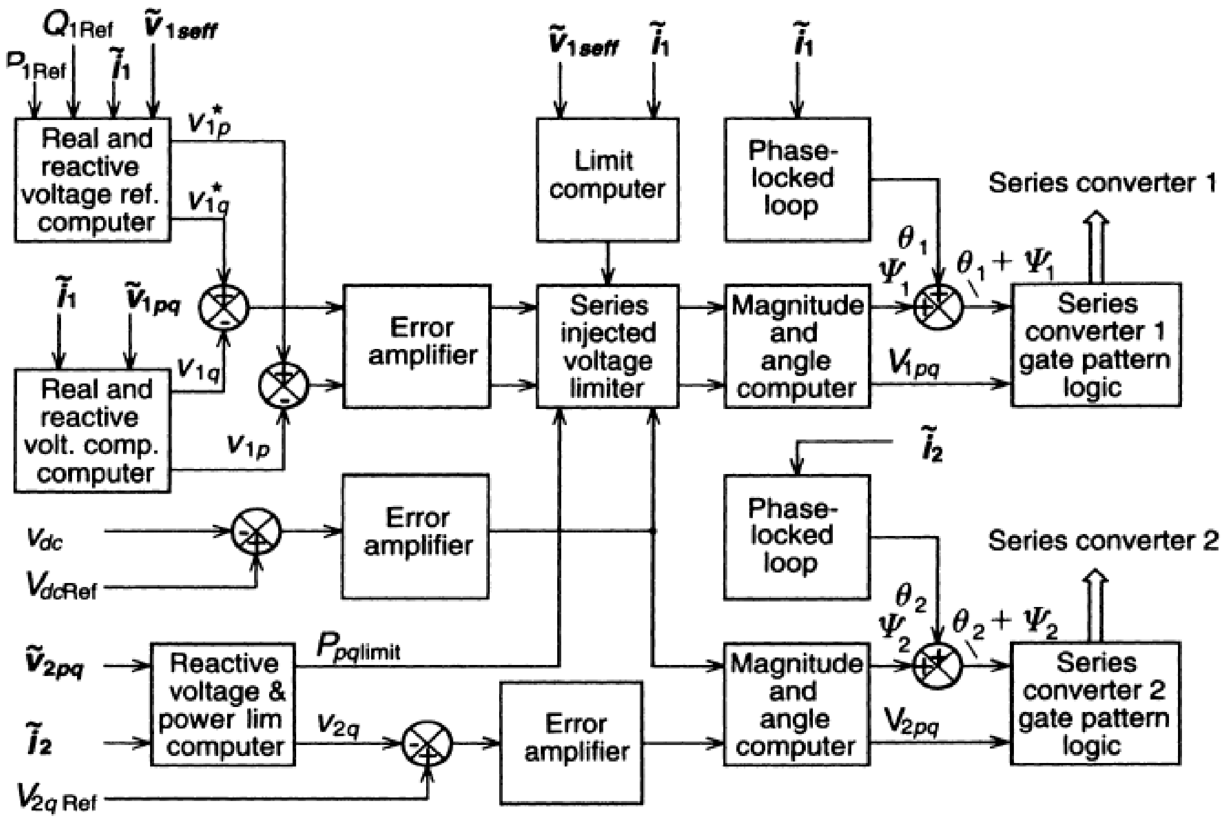


Figure 6.6 Basic control schemes for a two-converter IPFC.

As shown in Figure 6.6 the operation of Converter 1 is synchronized to line current i_1 and Converter 2 to line current i_2 by two independent phase-locked loops. This enables each converter to provide independent series reactive compensation and to keep operating under contingency conditions when the other line or converter is out of service. The input to the "prime" control is either the desired real and reactive line power, P_1 and Q_l (indicated in the fig. by P_{1Ref} and Q_{1Ref}) or it could be the desired quadrature and real compensating voltage V_{lq} and V_{1p}, shown in the figure as internal references, V^*_{1p} and V^*_{1q}, derived from $P_1$and Q_l. Voltage component $V^*_{1q,}$ being in quadrature with the prevailing line current i_1, represents series reactive compensation to control the transmitted real power, and component V^*_{1p}, being in phase with that, represents series real compensation to control the reactive power flow in the line.

6.9 Applications:

(1) The IPFC is particularly advantageous when controlled series compensation or other series power flow control (e.g., phase shifting) is contemplated. This is because the IPFC simply combines the otherwise independent series compensators (SSSCs), without any significant hardware addition, and affords some of those a greatly enhanced functional capability. The increased functional capability can be moved from one line to another, as system conditions may dictate. In addition, the individual converters of the IPFC can be decoupled and operated as independent series reactive compensators, without any hardware change.

(2) Although converters with different dc voltage could be coupled via appropriate dc-to-dc converters ("choppers"), the arrangement would be expensive with relatively high operating losses. Therefore, it is desirable to establish a common dc operating voltage for all converter-based Controllers used at one location, which would facilitate their dc coupling and thereby an inexpensive extension of their functional capabilities. Reasonably defined common dc operating voltage should not impose significant restriction on the converter design, since at high output power multiple parallel poles are normally employed. Apart from the potential for dc coupling, common operating voltage would also be helpful for the standardization of the converter type equipment used at one location, as well as for the maintenance of spare parts inventory.

(3) The operating regions of the individual converters of the IPFC can differ significantly, depending on the voltage and power ratings of the individual lines and on the amount of compensation desired. It is evident that a high voltage/ high-power line may supply the necessary real power for a low voltage/ low-power capacity line to optimize its power transmission, without significantly affecting its own transmission.

(4) The IPFC is an ideal solution to balance both the real and reactive power flow in multiline and meshed systems.

(5) The prime converters of the IPFC can be controlled to provide totally different operating functions, e.g., independent *(P)* and *(Q)* control, phase shifting (transmission angle regulation), transmission impedance control, etc. These functions can be selected according to prevailing system operating requirements.
