

FACTS: flexible alternating current transmission systems

Report

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FACTS

Flexible Alternating Current Transmission Systems

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Increased demands on transmission, absence of long-term planning and the need to provide open access to generating companies and customers have created tendencies toward less security and reduced quality of supply. The FACTS technology is essential to alleviate some but not all of these difficulties.

The FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded, lines. The possibility that current and therefore power through a line can be controlled enables a large potential of increasing the capacity of existing lines. These opportunities arise through the ability of FACTS controllers to control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle and the damping of oscillations.

This report is an overview of the existing FACTS devices. It is mainly a summary of [1], [2], [3] where more extensive elaborations on FACTS devices can be found. The IEEE definition to these devices are given in italic in the corresponding sections.

1 Static Shunt Compensators

Shunt compensation is used to influence the natural electrical characteristics of the transmission line to increase the steady-state transmittable power and to control the voltage profile along the line.

As static shunt compensators are known Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM). The IEEE-definition of a SVC is as follows:

Static Var Compensator (SVC): *A shunt-connected static var generator or 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).*

SVC is an umbrella term for several devices. The SVC devices discussed in the following sections are the TCR, TSR and TSC. The characteristics of a SVC are described as

- based on normal inductive and capacitive elements
- not based on rotating machines
- control function is through power electronics.

The STATCOM which is discussed in Sect. 1.3 has the following characteristics

- based on voltage source synchronized to network
- not based on rotating machines
- control function is based on adjustment of voltage.

By placing the shunt in the middle of a line and therefore dividing the line into two segments, the voltage at this point can be controlled such that it has the same value as the end line voltages. This has the advantage that the maximal power transmission is increased.

If the shunt compensator is located at the end of a line in parallel to a load it is possible to regulate the voltage at this end and therefore to prevent voltage instability caused by load variations or generation or line outages.

As shunt compensation is able to change the power flow in the system by varying the value of the applied shunt compensation during and following dynamic disturbances the transient stability limit can be increased and effective power oscillation damping is provided. Thereby the voltage of the transmission line counteracts the accelerating and decelerating swings of the disturbed machine and therefore dampens the power oscillations.

1.1 Thyristor-Controlled and Thyristor-Switched Reactor (TCR and TSR)

TCR: *A shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor value.*

An elementary single-phase thyristor-controlled reactor (TCR) is shown in Fig. 1. The current in the reactor can be controlled from maximum to zero by the method of firing delay angle control. That is the duration of the current conduction intervals is controlled by delaying the closure of the thyristor valve with respect to the peak of the applied voltage in each half-cycle (Fig. 1). For $\alpha = 0^\circ$ the amplitude is at its maximum and for $\alpha = 90^\circ$ the amplitude is zero and no current is flowing during the corresponding half-cycle. Like this the same effect is provided as with an inductance of changing value.

A thyristor switched reactor (TSR) has similar equipment to a TCR, but is used only at fixed angles of 90° and 180° , i.e. full conduction or no conduction. The reactive current $i_S(t)$ will be proportional to the applied voltage. Several TSRs can provide a reactive admittance controllable in a step-like manner.

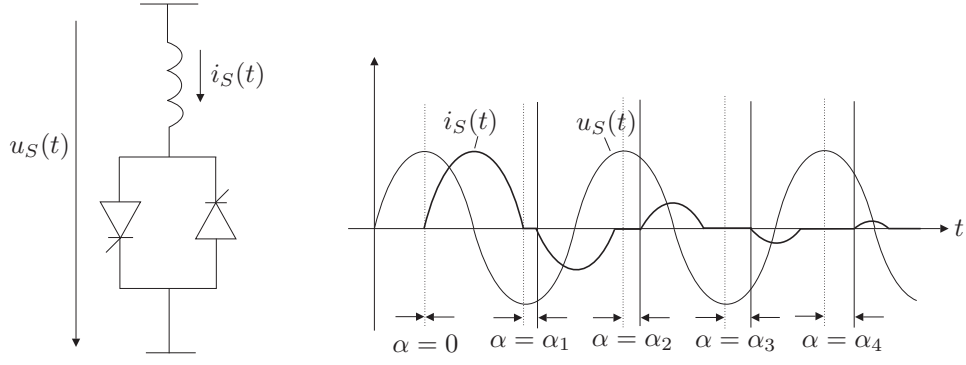
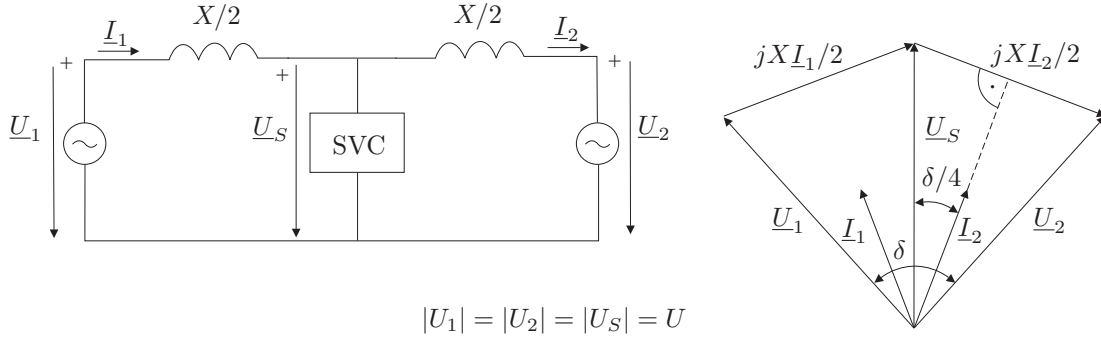


Figure 1: Thyristor-Controlled Reactor

TSR: A shunt-connected, thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor value.

If a TSR or TCR is placed in the middle of the line to keep the voltage at this place at the same value as at the ends of the line the maximal transmittable power is doubled. This can be shown considering the diagram in Fig. 2



$$|U_1| = |U_2| = |U_S| = U$$

Figure 2: Two machine system with SVC in the middle

It is assumed that the end line voltages and the midline voltage all have the same magnitude U . The phasor angle of U_2 is set to zero and therefore is used as reference value for the other phasors.

$$\underline{U}_2 = U, \quad \underline{U}_1 = Ue^{j\delta}, \quad \underline{U}_S = Ue^{j\delta/2} \quad (1)$$

With some trigonometry, \underline{I}_2 can be calculated as

$$\underline{I}_2 = \frac{4U}{X} \sin \delta/4 \cdot e^{j\delta/4} \quad (2)$$

The transmitted power results in

$$P = \Re \{ \underline{U}_1 \cdot \underline{I}_1^* \} = \Re \{ \underline{U}_2 \cdot \underline{I}_2^* \} \quad (3)$$

$$= \Re \left\{ \frac{4U^2}{X} \sin(\delta/4) (\cos(\delta/4) - j \sin(\delta/4)) \right\} \quad (4)$$

$$= \frac{2U^2}{X} \sin(\delta/2) \quad (5)$$

As the transmitted power without the SVC is $\frac{U^2}{X} \sin(\delta)$ the maximal transmittable power is doubled from $\frac{U^2}{X}$ to $2\frac{U^2}{X}$.

In the previous elaborations it was assumed that the SVC is able to provide the voltage $|U_S| = U$ at any transmission angle. If we look at the SVC as adjustable susceptance B_{SVC} , it is clear that there are limits on the value of this susceptance. The larger the transmission angle the larger the necessary susceptance, because at the same voltage a higher current has to be provided. If the susceptance value reaches the upper limit Eq. 5 does not hold any more.

In Fig. 3 the impedance scheme of the system is shown as full lines. This scheme can be transformed by ‘‘Y-D’’ transformation into the dash-dotted system.

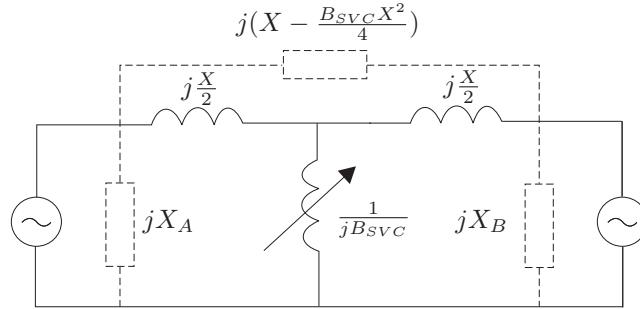


Figure 3: Equivalent network of the two machine system

The parallel reactances X_A and X_B do not play any role in this case because the U_1 and U_2 are assumed constant. Therefore, the transmitted power is

$$P = P_1 = P_2 = \frac{U_1 U_2}{X - \frac{X^2 B_{SVC}}{4}} \quad (6)$$

This results in a transmitted power versus transmission angle characteristic as shown in Fig. 4.

As long as the SVC is able to provide the same voltage as the end line voltages the characteristic follows the $|U_S| = U$ line up to the point where this line crosses the line of the maximal possible B_{SVC} . From this point the characteristic follows the line of the maximal possible B_{SVC} . For example, if the maximal value for B_{SVC} is $4X \cdot 0.4$, the characteristic corresponds to the $|U_S| = U$ line up to δ_c and then continues on the $B_{SVC} = 4X \cdot 0.4$ line. For the other SVC the characteristic looks the same as they all are based on the same concept of inserting a shunt reactance into the line.

From Fig. 1 it can be seen that the firing angle control results in a nonsinusoidal current waveform in the reactor. Thus, in addition to the wanted fundamental current, also harmonics are generated. If the positive and negative current half-cycles are identical, only odd harmonics are generated and the amplitudes are

$$I_{Sn}(\alpha) = \frac{U}{\omega L} \frac{4}{\pi} \left\{ \frac{\sin \alpha \cos(n\alpha) - n \cos \alpha \sin(n\alpha)}{n(n^2 - 1)} \right\} \quad (7)$$

where $n = 2k + 1, k = 1, 2, 3, \dots$

In a three-phase system, three single-phase thyristor-controlled reactors are used, usually in delta connection. Under balanced conditions, the triple- n harmonic currents

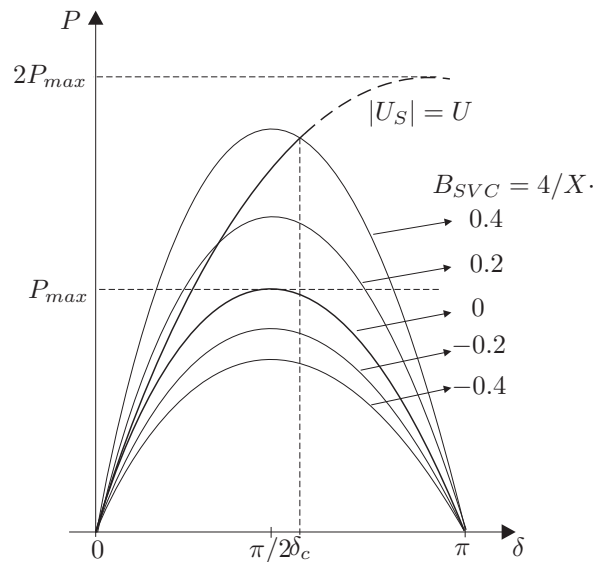


Figure 4: Transmitted power versus transmission angle characteristic for a SVC

(3rd, 9th, 15th, etc.) circulate in the delta connected TCRs and do not enter the power system. The magnitudes of the other harmonics generated by the thyristor-controlled reactors can be reduced by various methods.

One method employs m parallel-connected TCRs, each with $1/m$ of the total rating required (Fig. 5). The reactors are sequentially controlled, i.e. only one of the m reactors is delay angle controlled, and each of the remaining $m - 1$ reactors is either fully “on” or fully “off” depending on the total reactive power required. Like this the amplitude of every harmonic is reduced by the factor m with respect to the maximum rated fundamental current.

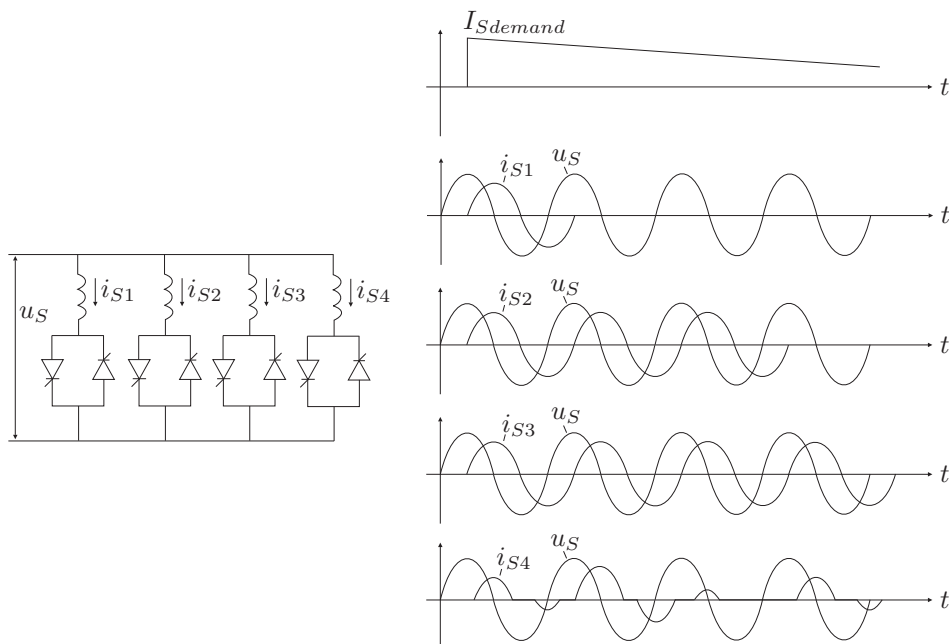


Figure 5: Method for controlling four TCR banks to achieve harmonic reduction

Another method employs a 12-pulse TCR arrangement. In this, two identical three-phase delta connected thyristor-controlled reactors are used, one operated from wye-connected windings, the other from delta-connected windings of the secondary of a coupling transformer. Because of the 30-degree phase shift between the related voltages of the two transformer windings, the harmonic currents of order $6(2k - 1)$ and $6(2k - 1) + 1$, $k = 1, 2, 3, \dots$ cancel, resulting in a nearly sinusoidal output current at all delay angles.

Further harmonic cancellation is possible by operating three or more delta connected TCRs from appropriately phase shifted voltage sets. In practice, these 18 and higher pulse circuit arrangements tend to be too complex and expensive.

If the TCR generated harmonics cannot be reduced sufficiently by circuit arrangements, such as the four-reactor system or the 12-pulse structure, harmonic filters are employed. Normally, these filters are series LC and LCR branches in parallel with the TCR and are tuned to the dominant harmonics.

1.2 Thyristor-Switched Capacitor (TSC)

TSC: *A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.*

In Fig. 6, a single-phase thyristor-switched capacitor (TSC) is shown. The TSC branch can be switched out at a zero crossing of the current. At this time instance the capacitor value has reached its peak value. The disconnected capacitor ideally stays charged at this peak value and the voltage across the nonconducting thyristor varies in phase with the applied ac voltage.

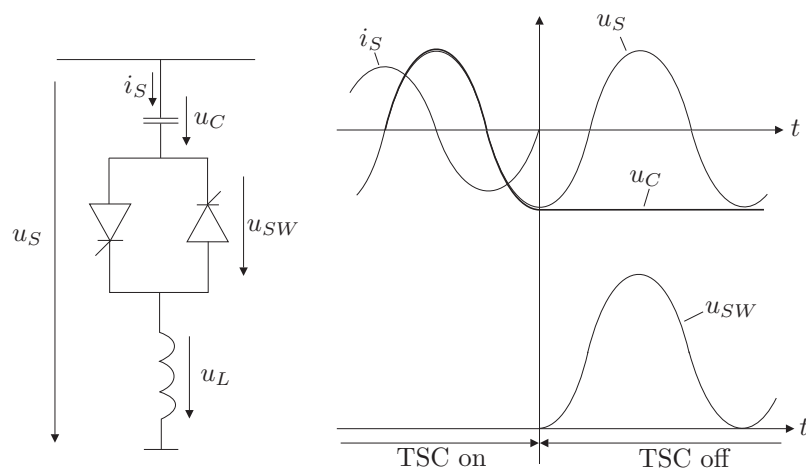


Figure 6: Thyristor-Switched Capacitor

Normally, the voltage across the capacitor does not remain constant during the time when the thyristor is switched out, but it is discharged after disconnection. To minimize transient disturbances when switching the TSC on, the reconnection has to take place at an instance where the AC voltage and the voltage across the conductor

are equal, that is when the voltage across the thyristor valve is zero. However, there will still be transients caused by the nonzero du_S/dt at the instant of switching, which, without the reactor, would result an instant current in the capacitor ($i_S = C \cdot du_S/dt$). The interaction between the capacitor and the current (and di_S/dt) limiting reactor produces oscillatory transients on current and voltage.

From these elaborations it follows that firing delay angle control is not applicable to capacitors; the capacitor switching must take place at that specific instant in each cycle at which the conditions for minimum transients are satisfied. For this reason, a TSC branch can provide only a step-like change in the reactive current it draws (maximum or zero). Thus, the TSC is a single capacitive admittance which is either connected to or disconnected from the AC system. The current through the capacitor varies with the applied voltage. To approximate continuous current variations, several TSC branches in parallel may be used.

1.3 Static synchronous compensator: STATCOM

STATCOM: *A static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the AC system voltage.*

A STATCOM is a controlled reactive-power source. It provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors or capacitor banks. The basic voltage-source converter scheme is shown in Fig. 7.

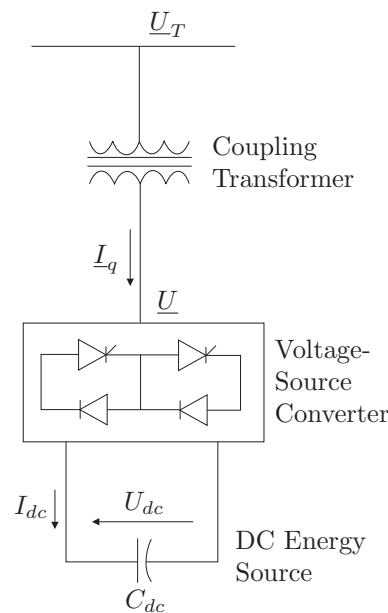


Figure 7: Static Synchronous Compensator

The charged capacitor C_{dc} provides a DC voltage to the converter, which produces a set of controllable three-phase output voltages with the frequency of the AC power system. By varying the amplitude of the output voltage \underline{U} , the reactive power exchange

between the converter and the AC system can be controlled. If the amplitude of the output voltage \underline{U} is increased above that of the AC system \underline{U}_T , a leading current is produced, i.e. the STATCOM is seen as a conductor by the AC system and reactive power is generated. Decreasing the amplitude of the output voltage below that of the AC system, a lagging current results and the STATCOM is seen as an inductor. In this case reactive power is absorbed. If the amplitudes are equal no power exchange takes place.

A practical converter is not lossless. In the case of the DC capacitor, the energy stored in this capacitor would be consumed by the internal losses of the converter. By making the output voltages of the converter lag the AC system voltages by a small angle, the converter absorbs a small amount of active power from the AC system to balance the losses in the converter.

The mechanism of phase angle adjustment can also be used to control the reactive power generation or absorption by increasing or decreasing the capacitor voltage U_{dc} , and thereby the output voltage \underline{U} .

Instead of a capacitor also a battery can be used as DC energy. In this case the converter can control both reactive and active power exchange with the AC system. The capability of controlling active as well as reactive power exchange is a significant feature which can be used effectively in applications requiring power oscillation damping, to level peak power demand, and to provide uninterrupted power for critical load.

The derivation of the formula for the transmitted active power employs considerable calculations. Using the variables defined in Fig. 8 and applying Kirchoffs laws the following equations can be written

$$\underline{I}_2 = \frac{\underline{U}_T - \underline{U}_2}{jX_2} = \frac{(\underline{U}_1 - j\underline{I}_1 X_1) - \underline{U}_2}{jX_2} \quad (8)$$

$$\underline{I}_2 = \underline{I}_1 - \underline{I}_q \quad (9)$$

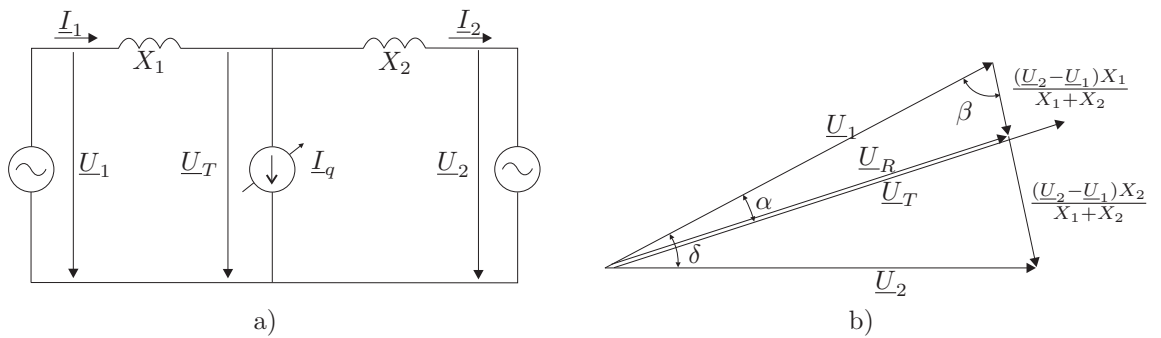


Figure 8: Two machine system with STATCOM

By equalling right-hand terms of (8) and (9), a formula for the current \underline{I}_1 is obtained

$$\underline{I}_1 = \frac{\underline{U}_1 - \underline{U}_2}{j(X_1 + X_2)} + \underline{I}_q \frac{X_2}{(X_1 + X_2)} \quad (10)$$

From this, the voltage \underline{U}_T is derived as

$$\underline{U}_T = \underline{U}_1 - j\underline{I}_1 X_1 \quad (11)$$

$$= \underline{U}_1 - \frac{(\underline{U}_1 - \underline{U}_2)X_1}{(X_1 + X_2)} - j\underline{I}_q \cdot \frac{X_1 X_2}{(X_1 + X_2)} \quad (12)$$

$$= \underline{U}_R - j\underline{I}_q \cdot \frac{X_1 X_2}{X_1 + X_2} \quad (13)$$

where \underline{U}_R is the STATCOM terminal voltage if the STATCOM is out of operation, i.e. when $\underline{I}_q = 0$. The fact that \underline{I}_q is shifted by 90° with regard to \underline{U}_R can be used to express \underline{I}_q as

$$\underline{I}_q = jI_q \cdot \frac{\underline{U}_R}{U_R}. \quad (14)$$

Equation (13) is then rewritten as follows

$$\underline{U}_T = \underline{U}_R + I_q \frac{\underline{U}_R}{U_R} \cdot \frac{X_1 X_2}{(X_1 + X_2)} = \underline{U}_R \left(1 + \frac{I_q}{U_R} \cdot \frac{X_1 X_2}{(X_1 + X_2)} \right) \quad (15)$$

Applying the sine law to the diagram in Fig. 8, the following two equations result

$$\frac{\sin \beta}{U_2} = \frac{\sin \delta}{|\underline{U}_1 - \underline{U}_2|} \quad (16)$$

$$\frac{\sin \alpha}{|\underline{U}_1 - \underline{U}_2| \frac{X_1}{(X_1 + X_2)}} = \frac{\sin \beta}{U_R} \quad (17)$$

from which the formula for $\sin \alpha$ is derived

$$\sin \alpha = \frac{U_2 \sin \delta X_1}{U_R (X_1 + X_2)}. \quad (18)$$

The formula for the transmitted active power can be given as

$$P = P_1 = P_2 = \frac{U_T U_1}{X_1} \sin \alpha = \frac{U_1 U_2 \sin \delta}{(X_1 + X_2)} \cdot \frac{U_T}{U_R} \quad (19)$$

To dispose of the term U_R the cosine law is applied to the diagram in Fig. 8 b). Therefore,

$$U_R = |\underline{U}_R| = \left| \frac{\underline{U}_1 X_2 + \underline{U}_2 X_1}{(X_1 + X_2)} \right| = \frac{\sqrt{U_1^2 X_2^2 + U_2^2 X_1^2 + 2U_1 U_2 X_1 X_2 \cos \delta}}{(X_1 + X_2)} \quad (20)$$

Substituting this and (15) into (19) and performing some algebraic calculations, the final formula for the transmitted active power is obtained

$$P = \frac{U_1 U_2 \sin \delta}{(X_1 + X_2)} \cdot \frac{\left| \underline{U}_R \left(1 + \frac{I_q}{U_R} \cdot \frac{X_1 X_2}{X_1 + X_2} \right) \right|}{U_R} = \frac{U_1 U_2 \sin \delta}{(X_1 + X_2)} \left(1 + \frac{I_q}{U_R} \cdot \frac{X_1 X_2}{(X_1 + X_2)} \right) \quad (21)$$

The resulting characteristic of the transmitted power versus transmission angle is given in Fig. 9.

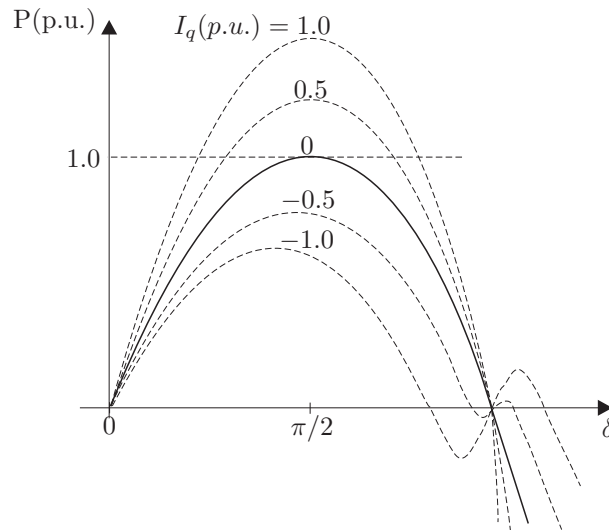


Figure 9: Transmitted power versus transmission angle characteristic of a STATCOM

1.4 Comparison of Shunt Compensators

SVC and STATCOM are very similar in their functional compensation capability, but the basic operating principles are fundamentally different. A STATCOM functions as a shunt-connected synchronous voltage source whereas a SVC operates as a shunt-connected, controlled reactive admittance. This difference accounts for the STATCOM's superior functional characteristics, better performance, and greater application flexibility than those attainable with a SVC.

In the linear operating range the V-I characteristic (Fig. 10) and functional compensation capability of the STATCOM and the SVC are similar. Concerning the non-linear operating range, the STATCOM is able to control its output current over the rated maximum capacitive or inductive range independently of AC system voltage, whereas the maximum attainable compensating current of the SVC decreases linearly with AC voltage. Thus, the STATCOM is more effective than the SVC in providing voltage support under large system disturbances during which the voltage excursions would be well outside of the linear operating range of the compensator. The ability of the STATCOM to maintain full capacitive output current at low system voltage also makes it more effective than the SVC in improving the transient stability.

The attainable response time and the bandwidth of the closed voltage regulation loop of the STATCOM are also significantly better than those of the SVC.

In situations where it is necessary to provide active power compensation the STATCOM is able to interface a suitable energy storage (large capacitor, battery, ...) from where it can draw active power at its DC terminal and deliver it as AC power to the system. On the other side, the SVC does not have this capability.

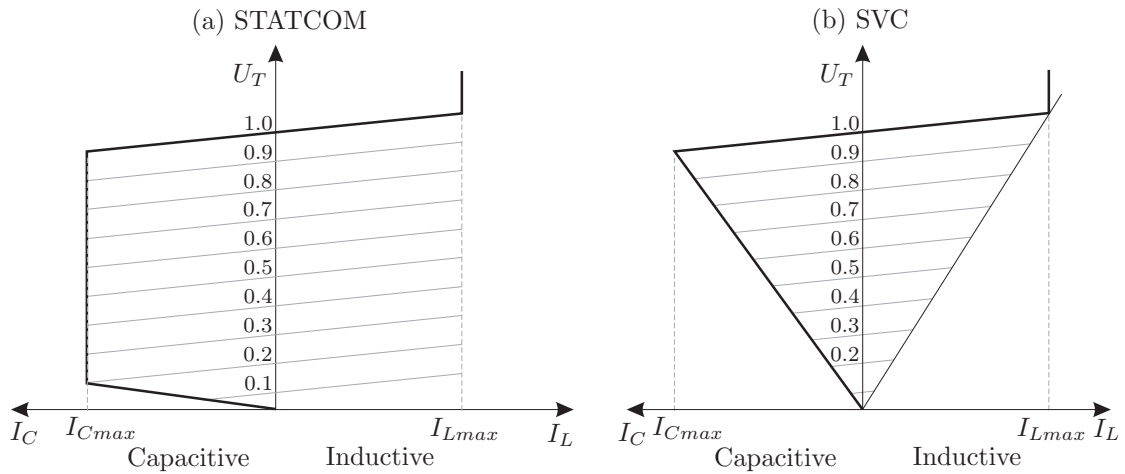


Figure 10: V-I characteristics of the STATCOM (a) and the SVC (b)

2 Static Series Compensators

The variable series compensation is highly effective in both controlling power flow in the line and in improving stability. With series compensation the overall effective series transmission impedance from the sending end to the receiving end can be arbitrarily decreased thereby influencing the power flow ($P = U^2/X \sin \delta$). This capability to control power flow can effectively be used to increase the transient stability limit and to provide power oscillation damping.

2.1 Thyristor-Switched Series Capacitor (TSSC)

The basic element of a TSSC is a capacitor shunted by bypass valve shown in Fig. 11. The capacitor is inserted into the line if the corresponding thyristor valve is turned off, otherwise it is bypassed.

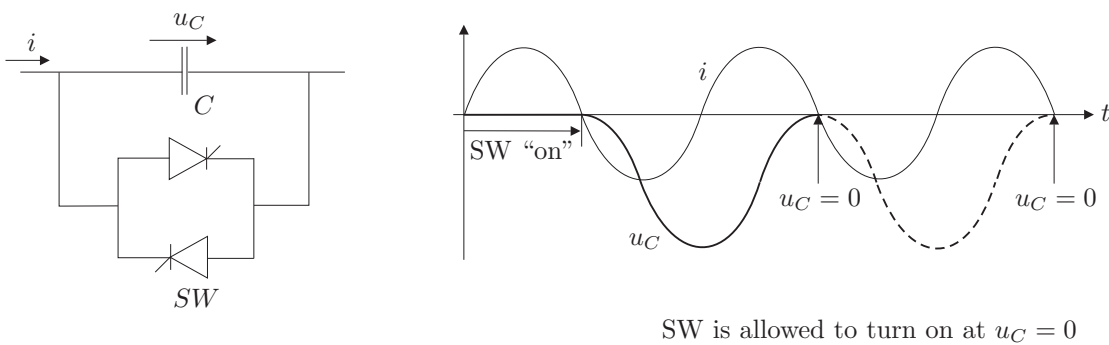


Figure 11: Course of capacitor voltage for a basic element in a TSSC

A thyristor valve is turned off in an instance when the current crosses zero. Thus, the capacitor can be inserted into the line by the thyristor valve only at the zero crossings of the line current. On the other hand, the thyristor valve should be turned on for bypass only when the capacitor voltage is zero in order to minimize the initial

surge current in the valve, and the corresponding circuit transient. This results in a possible delay up to one full cycle to turn the valve on.

Therefore, if the capacitor is once inserted into the line, it will be charged by the line current from zero to maximum during the first half-cycle and discharged from maximum to zero during the successive half-cycle until it can be bypassed again. This is illustrated in Fig. 11.

A Thyristor-Switched Series Capacitor is built from several of these basic elements in series (Fig. 12). The degree of series compensation is controlled in a step-like manner by increasing or decreasing the number of series capacitors inserted. Thus, a TSSC can only provide discrete capacitor values for series compensation. A TSSC can be applied for power flow control and for damping power oscillations.

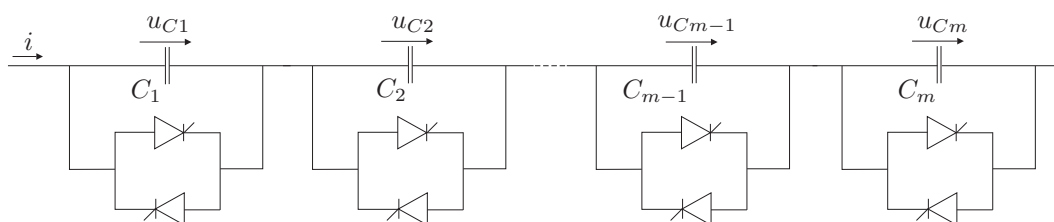


Figure 12: Thyristor-Switched Series Capacitor

The TSSC can be considered as a controllable reactance in series with the line reactance as shown in Fig. 13 a). The ratio of the inserted TSSC reactance to the line reactance

$$K = -\frac{X_{TSSC}}{X} \quad (22)$$

is a measure for the compensation degree of the line.

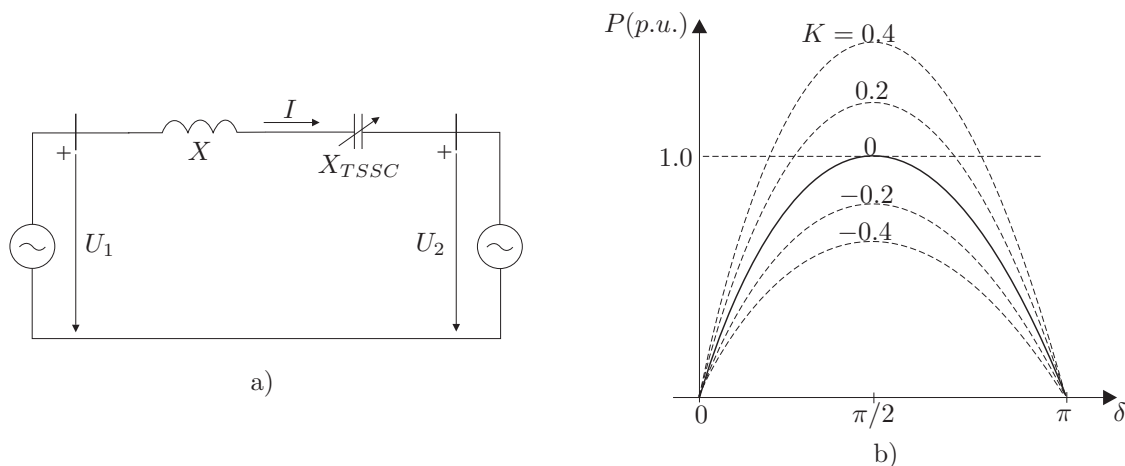


Figure 13: a) Two machine system with TSSC and b) corresponding transmitted power versus angle characteristics

The transmitted active power is calculated from the general formula for transmitted active power on a line and is given as

$$P = \frac{U_1 U_2}{X + X_{TSSC}} \sin \delta = \frac{U_1 U_2}{X(1 - K)} \sin \delta. \quad (23)$$

Thus, the transmitted active power versus angle characteristic for a TSSC is shown in Fig. 13 b). It can be seen that the value of K determines the maximal transmittable power.

The influence of a change in K on the change of transmitted active power P at different values of P , can be derived from the derivative of (23) with respect to K

$$\frac{\partial P}{\partial K} = \frac{U_1 U_2}{X(1-K)^2} \sin \delta \quad (24)$$

$$= \frac{P}{1-K} \quad (25)$$

Thus, $\frac{\partial P}{\partial K}$ is proportional to P resulting in the graphic in Fig. 14 a) where it is assumed that K is fixed. The slope of the curve depends on the compensation, i.e. on K according to (25).

The assumption of a fixed K is not exactly correct, because $\frac{\partial P}{\partial K}$ is a figure for how much the transmitted power changes if K changes. Therefore, the elaborations above are only true for small changes in K . Further considerations can be done by

$$\frac{\partial P}{\partial K} = \frac{P}{1-K} = P \cdot \frac{P}{P_0} \quad (26)$$

where

$$P_0 = \frac{U_1 U_2}{X} \sin(\delta). \quad (27)$$

Therefore, $\frac{\partial P}{\partial K}$ is proportional to the square of the transmitted power P . Assuming a fixed P_0 the graph in Fig. 14 b) results.

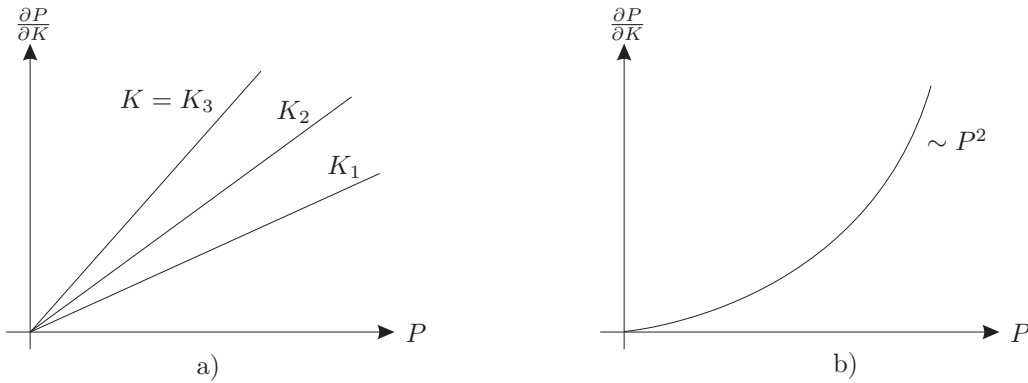


Figure 14: $\frac{\partial P}{\partial K}$ versus P for a) fixed K and b) fixed P_0

2.2 Thyristor-Controlled Series Capacitor (TCSC)

TCSC: *A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance.*

The scheme of a Thyristor-Controlled Series Capacitor is given in Fig. 15. A parameter to describe the TCSC main circuit is λ which is the quotient of the resonant frequency and the network frequency resulting in

$$\lambda = \sqrt{\frac{-X_C}{X_L}}, \quad (28)$$

where $X_C = -\frac{1}{\omega C}$ and $X_L = \omega L$. Reasonable values for λ fall in the range of 2 to 4.

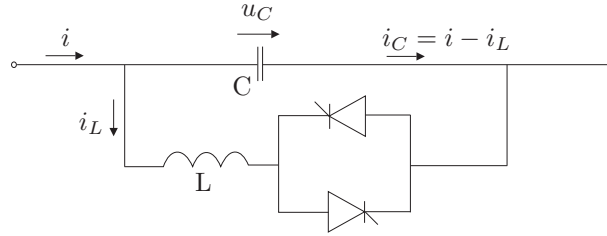


Figure 15: Thyristor-Controlled Series Capacitor (TCSC)

The operating modes of a TCSC are characterized by the so-called boost factor

$$K_B = \frac{X_{TCSC}}{X_C}, \quad (29)$$

where X_{TCSC} is the apparent reactance ($X_{TCSC} = \Im \left\{ \frac{U_C}{I} \right\}$).

1. **Blocking mode:** The thyristor valve is not triggered and the thyristors are kept in nonconducting state. The line current passes only through the capacitor bank ($X_{TCSC} = X_C$). Thus, the boost factor is equal to one. In this mode the TCSC performs like a fixed series capacitor.
2. **Bypass mode:** The thyristor valve is triggered continuously and therefore the valve stays conducting all the time. The TCSC behaves like a parallel connection of the series capacitor and the inductor. As

$$X_{TCSC} = \frac{X_L X_C}{X_L + X_C} = \frac{-X_C}{1 - \lambda^2} \quad (30)$$

the voltage is inductive and the boost factor is negative. When λ is considerably larger than unity the amplitude of u_C is much lower in bypass than in blocking mode. Therefore, the bypass mode is utilized to reduce the capacitor stress during faults.

3. **Capacitive boost mode:** If a trigger pulse is supplied to the thyristor having forward voltage just before the capacitor voltage crosses the zero line a capacitor discharge current pulse will circulate through the parallel inductive branch. The discharge current pulse adds to the line current through the capacitor bank. It causes a capacitor voltage that adds to the voltage caused by the line current. The capacitor peak voltage thus will be increased in proportion to the charge

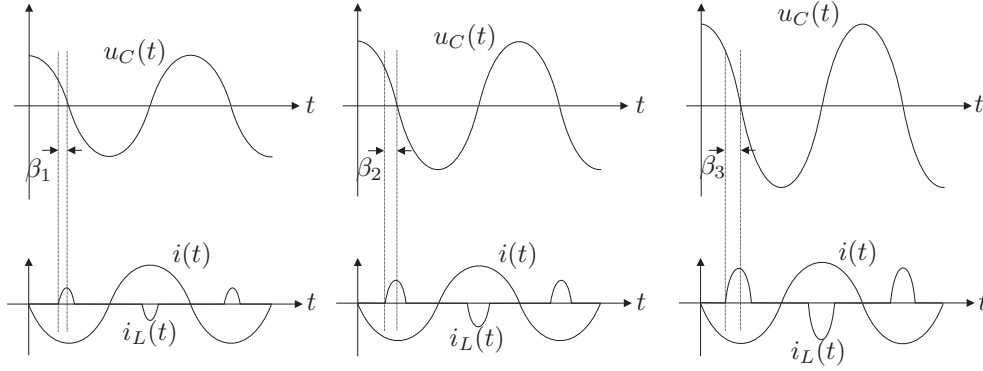


Figure 16: Waveforms at various boost factors in capacitive boost mode

that passes through the thyristor branch. The charge depends on the conduction angle β (Fig. 16).

For the boost factor, the mathematical formula is (without giving the derivation)

$$K_B = 1 + \frac{2}{\pi} \frac{\lambda^2}{\lambda^2 - 1} \left[\frac{2 \cos^2 \beta}{\lambda^2 - 1} (\lambda \tan \lambda \beta - \tan \beta) - \beta - \frac{\sin 2\beta}{\beta} \right]. \quad (31)$$

Due to the factor $\tan(\lambda\beta)$ this formula has an asymptote at $\beta_\infty = \frac{\pi}{2\lambda}$. The TCSC operates in the capacitive boost mode when $0 < \beta < \beta_\infty$. An example boost factor versus conduction angle characteristic is given in Fig. 17.

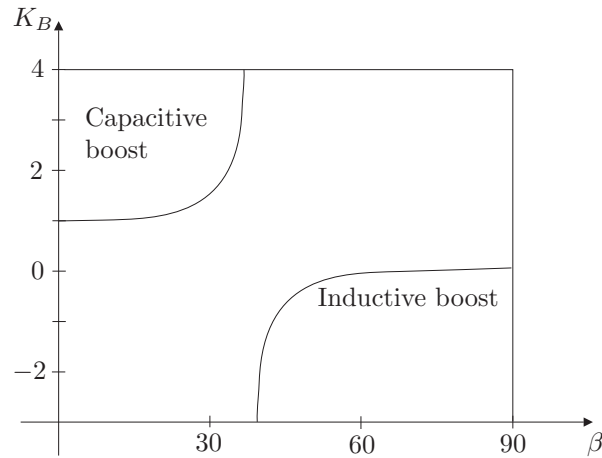


Figure 17: Boost factor versus conduction angle

4. **Inductive boost mode:** If the conduction angle is increased above β_∞ the mode changes from capacitive to inductive boost mode (Fig. 17). In the inductive boost mode, large thyristor currents may occur. The curves of the currents and the voltage for three different conduction angles are given in Fig. 18. The capacitor voltage waveform is very much distorted from its desired sinusoidal shape. Because of this waveform and the high valve stress, the inductive boost mode is less attractive for steady state operation.

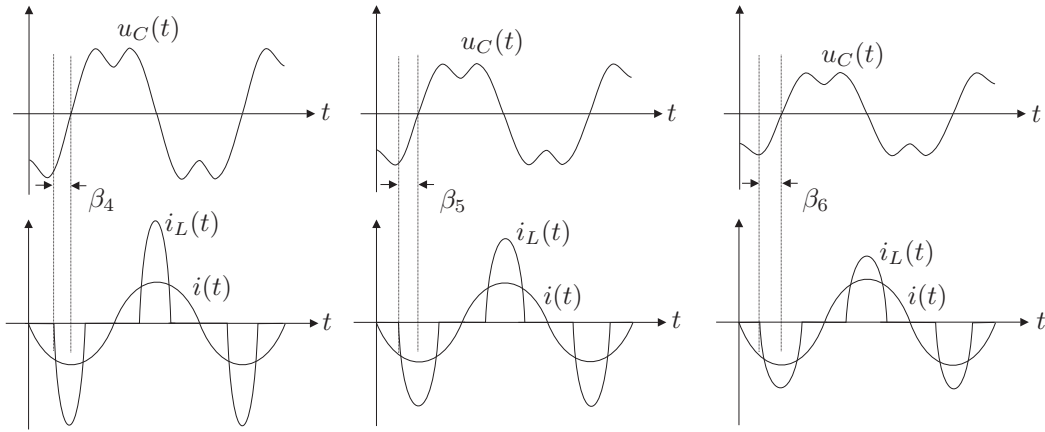


Figure 18: Waveforms at various boost factors in inductive boost mode

Because a TCSC is based on the same idea as the TSSC, namely to introduce additional reactances, the characteristics of the transmitted power versus transmission angle looks alike the one of the TSSC in Fig. 13 and also the $\frac{\partial P}{\partial K}$ is the same (Fig. 14).

2.3 GTO Thyristor-Controlled Series Capacitor (GCSC)

An elementary GTO Thyristor-Controlled Series Capacitor consists of a fixed capacitor with a GTO thyristor valve that has the capability to turn on and off upon command. The structure is given in Fig. 19. The objective of the GCSC scheme is to control the AC voltage u_C across the capacitor at a given line current i . When the GTO is closed u_C is zero and when it is open u_C is at its maximum. For controlling the capacitor voltage, the closing and opening of the valve is carried out in each half-cycle in synchronism with the AC system frequency. The GTO valve is stipulated to close automatically whenever the capacitor voltage crosses zero. The turning off of the valve is controlled by a delay angle γ with respect to the peak of the line current. Therefore, the adjustment of the capacitor voltage can only take place once in each half-cycle. This is shown in Fig. 19. Like this the effect of a capacitor with controllable reactance is introduced.

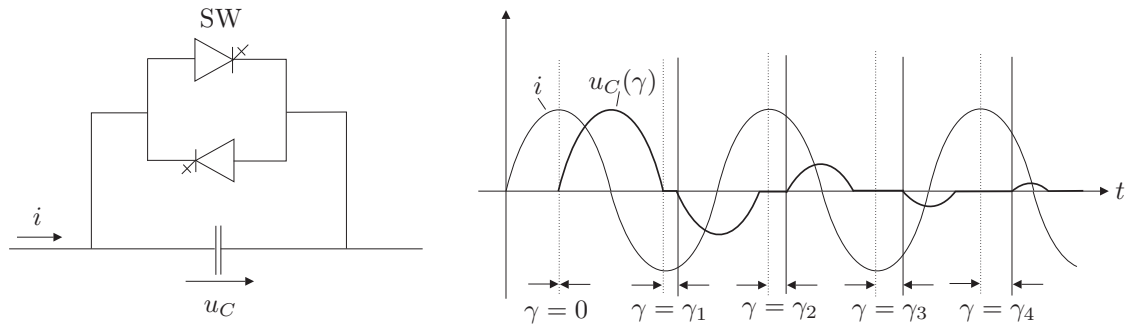


Figure 19: GTO-Controlled Series Capacitor

It can be seen from Figs. 1 and 19 that the waveforms for the current through the inductance of a TCR is identical to the waveform of the conductor voltage of the

GCSC and visualizes the duality of TCR and GCSC. Thus, it is obvious that the turn-off delay angle control of the GCSC generates harmonics like the turn-on delay angle control of the TCR. The amplitudes of the harmonics are

$$U_{Ln}(\alpha) = \frac{I}{\omega C} \frac{4}{\pi} \left\{ \frac{\sin \gamma \cos(n\gamma) - n \cos \gamma \sin(n\gamma)}{n(n^2 - 1)} \right\} \quad (32)$$

where $n = 2k + 1, k = 1, 2, 3, \dots$. The magnitudes of these harmonic frequencies can be attenuated effectively by the complementary application of the method of “sequential control” introduced in Sect. 1.1 to reduce the harmonics generated by a TCR. Thus, m GCSC are connected in series each rated with $1/m$ of the total voltage rating. All but one of these m capacitors are “sequentially” controlled to be inserted or bypassed. The single capacitor is turn-off delay angle controlled to enable continuous voltage control over the total operating range.

In contrast to the TCR arrangement, where for economic reasons only a small number of parallel branches would be applied, it might even be a technical preference to break a single high-voltage valve into four or more series connected modules to realize practical GCSC.

For the transmitted active power versus transmission angle characteristic the same holds as for the TCSC, i.e. it is alike the one for the TSSC in Fig. 13.

2.4 Static Synchronous Series Compensator (SSSC)

Static-Synchronous Series Compensator (SSSC): *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 SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behavior of the power system by additional temporary active power compensation, to increase or decrease momentarily, the overall active (resistive) voltage drop across the line.*

A SSSC is a voltage-source converter-based series compensator. The principle of a SSSC is shown in Fig. 20 for a two machine system.

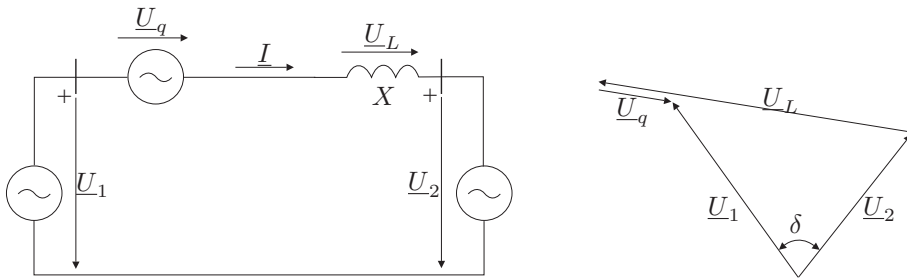


Figure 20: Synchronous voltage source for compensation

The phasor diagram shows that the voltage source increases the magnitude of the voltage across the inductance, i.e. the line, and therefore also increases the magnitude

of the current \underline{I} resulting in an increase in the power flow. This corresponds to the effect of a capacitor placed in series. By making the output voltage of the synchronous voltage source \underline{U}_q a function of the current \underline{I} , the same compensation as provided by the series capacitor is accomplished:

$$\underline{U}_q = -jX_C \underline{I}, \quad (33)$$

where X_C is the reactance of the capacitor. However, with a voltage source it is possible to maintain a constant compensating voltage in the presence of variable line current because the voltage can be controlled independently of the current, i.e. the voltage source can also decrease the voltage across the line inductance having the same effect as if the reactive line impedance was increased. Thus, the SSSC can decrease as well as increase the power flow to the same degree, simply by reversing the polarity of the injected AC voltage. The series reactive compensation scheme, using a switching power converter as a synchronous voltage is termed Static Synchronous Series Compensator.

The SSSC injects the compensating voltage in series with the line irrespective of the line current. As it is a reactive source, the phasor \underline{U}_T is perpendicular to the throughput current. Therefore, the current \underline{I} results in

$$\underline{I} = \frac{\underline{U}_1 - \underline{U}_q - \underline{U}_2}{jX} \quad (34)$$

$$= \frac{1}{jX} \left((\underline{U}_1 - \underline{U}_2) - U_q \cdot \frac{(\underline{U}_1 - \underline{U}_2)}{|\underline{U}_1 - \underline{U}_2|} \right) \quad (35)$$

$$= \frac{j(\underline{U}_2 - \underline{U}_1)}{X} \left(1 - \frac{U_q}{|\underline{U}_1 - \underline{U}_2|} \right). \quad (36)$$

The term $(\underline{U}_1 - \underline{U}_2)$ represents the phasor difference between \underline{U}_1 and \underline{U}_2 . Without source this would be the voltage drop on reactance X . The injected voltage \underline{U}_q phasor has the same direction as it is a reactive voltage source. This direction is determined by the term $(\underline{U}_1 - \underline{U}_2)/|\underline{U}_1 - \underline{U}_2|$. Multiplication with the injected voltage magnitude U_T mathematically describes the phasor \underline{U}_T . Choosing \underline{U}_2 as reference phasor, i.e. $\underline{U}_2 = U_2$, $\underline{U}_1 = U_1(\cos \delta + j \sin \delta)$, the transmission characteristic can be obtained from the following equation

$$P_1 = P_2 = P = \Re \{ \underline{U}_1 \underline{I}^* \} = \Re \{ \underline{U}_2 \underline{I}^* \} = U_2 \cdot \Re \{ \underline{I} \} \quad (37)$$

Taking into consideration that

$$|\underline{U}_1 - \underline{U}_2| = \sqrt{U_1^2 + U_2^2 - 2U_1U_2 \cos \delta} \quad (38)$$

the following formula results for the transmitted active power

$$P = \frac{U_1U_2 \sin \delta}{X} \left(1 - \frac{U_q}{\sqrt{U_1^2 + U_2^2 - 2U_1U_2 \cos \delta}} \right). \quad (39)$$

Therefore, the transmitted power P is a function of the injected voltage U_q . The transmitted power versus transmission angle characteristic is given in Fig. 21.

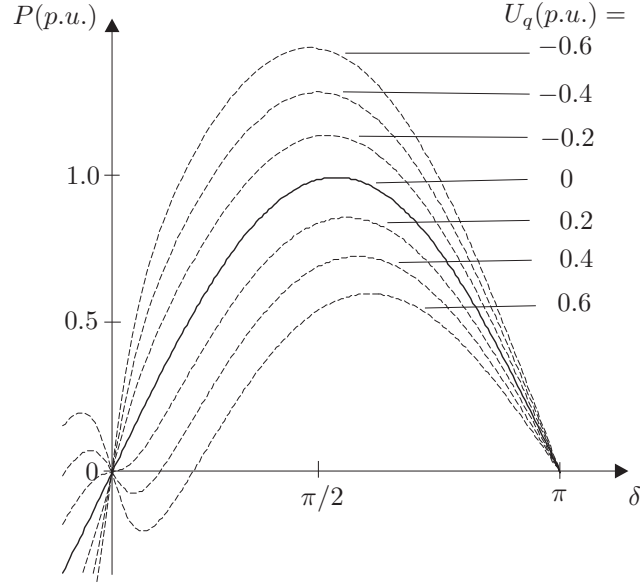


Figure 21: Transmitted power versus transmission angle provided by the SSSC

If the magnitudes of the end line voltages are equal, i.e. $U_1 = U_2 = U$, (39) results in

$$P = \frac{U^2}{X} \sin(\delta) - \frac{U}{X} U_q \cos(\delta/2) \quad (40)$$

The derivative of (40) with respect to U_q shows the influence of a change in U_q on the change of transmitted active power at different values of P :

$$\frac{\partial P}{\partial U_q} = \frac{P - P_0}{U_q} = -\frac{U}{X} \cos(\delta/2) \quad (41)$$

where

$$P_0 = \frac{U^2}{X} \sin(\delta) = P_0^{max} \cdot \sin(\delta). \quad (42)$$

With the trigonometric transformation

$$\cos(\delta/2) = \sqrt{\frac{1 + \cos(\delta)}{2}} = \sqrt{\frac{1 + \sqrt{1 - \sin^2(\delta)}}{2}} \quad (43)$$

and (42), $\frac{\partial P}{\partial U_q}$ results in

$$\frac{\partial P}{\partial U_q} = -\frac{U}{X} \cdot \sqrt{\frac{1 + \sqrt{1 - \sin^2(\delta)}}{2}} = -\frac{P_0^{max}}{U} \cdot \sqrt{\frac{1 + \sqrt{1 - \left(\frac{P_0}{P_0^{max}}\right)^2}}{2}} \quad (44)$$

Assuming that U and P_0^{max} are fixed, the graph for $\frac{\partial P}{\partial U_q}$ is given in Fig. 22.

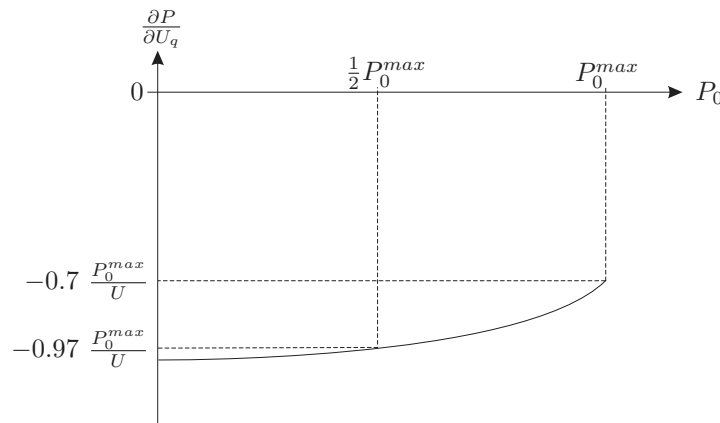


Figure 22: $\frac{\partial P}{\partial U_q}$ versus P for a SSSC

2.5 Phase Angle Regulator (PAR)

Phase Angle Regulators are able to solve problems referred to the transmission angle which cannot be handled by the other series compensators. Even though these regulators, based on the classical arrangement of tap-changing transformers, are not able to supply or absorb reactive power they are capable of exchanging active power with the power system. Additionally, modern voltage and phase angle regulators are used to improve the transient stability, to provide power oscillation damping and to minimize the post-disturbance overloads and the corresponding voltage dips.

In Fig. 23 the concept of a Phase Angle Regulator is shown. Theoretically, the Phase Angle Regulator can be considered a sinusoidal AC voltage source with controllable amplitude and phase angle. The angle of the voltage \underline{U}_σ relative to \underline{U}_1 is stipulated such that the magnitudes of \underline{U}_1 and $\underline{U}_{1\text{eff}}$ are equal.

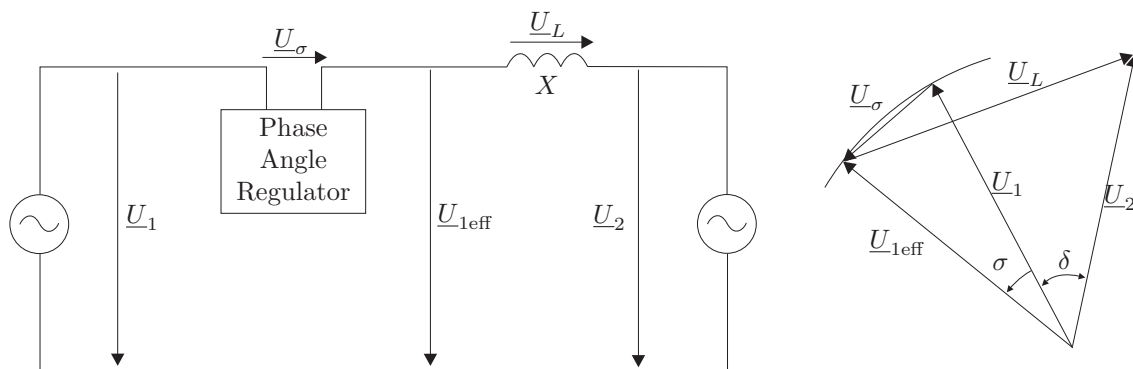


Figure 23: Phase Angle Regulator

The basic idea is to keep the transmitted power at the desired value independent of the prevailing transmission angle δ . If δ exceeds $\pi/2$ the amplitude of the voltage \underline{U}_σ is chosen such that the effective phase angle $\delta + \sigma$ between the sending- and receiving-end voltages stays at $\pi/2$. This is visualized in Fig. 24. The formulae for active and

reactive power are

$$P_\sigma = \frac{U_1 U_2}{X} \sin(\delta + \sigma) \quad (45)$$

$$Q_\sigma = \frac{U_1 U_2}{X} (1 - \cos(\delta + \sigma)) \quad (46)$$

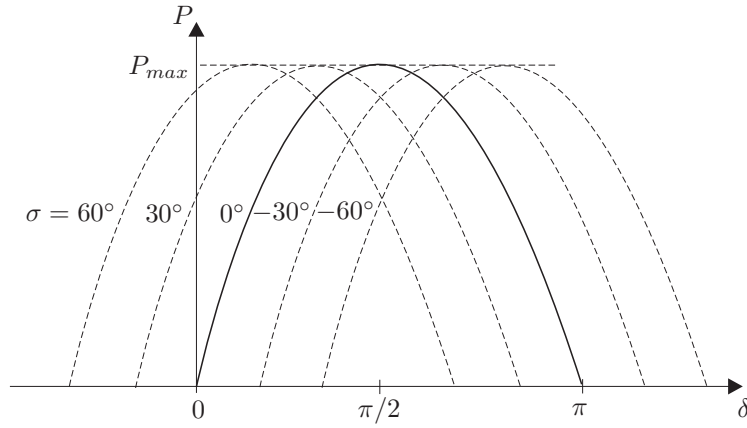


Figure 24: Transmitted power versus angle characteristics for a Phase Angle Regulator

To investigate the influence of a change in σ on the change of transmitted active power P at different values of P , the derivative of (45) with respect to σ is taken

$$\frac{\partial P}{\partial \sigma} = \frac{U_1 U_2}{X} \cos(\delta + \sigma) = \frac{U_1 U_2}{X} \sqrt{1 - \sin^2(\delta + \sigma)} \quad (47)$$

$$= \sqrt{\left(\frac{U_1 U_2}{X}\right)^2 - P^2} \quad (48)$$

From this and the assumption that $\frac{U_1 U_2}{X}$ is constant the graphic in Fig. 25 is drawn.

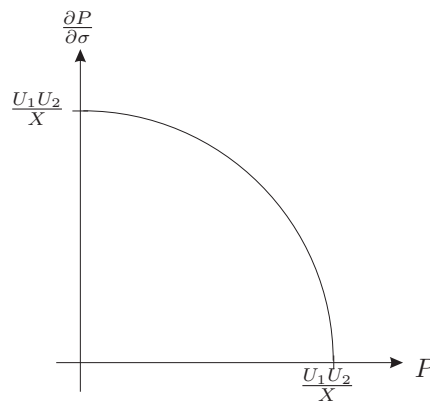


Figure 25: $\frac{\partial P}{\partial \sigma}$ versus P

This shows that for larger P the influence of a change in σ is rather small compared to the influence for a low transmitted active power.

2.6 Comparison of Series Compensators

The SSSC is a voltage source type and the TSSC, TCSC and GCSC are variable impedance type series compensators. Resulting from the different structures there are essential differences in characteristics and features of these devices [1]:

- The SSSC is capable of internally generating a controllable compensating voltage over an identical capacitive and inductive range independently of the magnitude of the line current. The compensating voltage of the GCSC and TSSC over a given control range is proportional to the line current. The TCSC can maintain maximum compensating voltage with decreasing line current over a control range determined by the current boosting capability of the thyristor-controlled reactor.
- The SSSC has the ability to interface with an external DC power supply to provide compensation for the line resistance by the injection of active power as well as for the line reactance by the injection of reactive power. The variable impedance type series compensators cannot exchange active power with the transmission line and can only provide reactive compensation.
- The SSSC with an energy storage increases the effectiveness of power oscillation damping by modulating the series reactive compensation to increase and decrease the transmitted power and by concurrently injecting an alternating virtual positive and negative real impedance to absorb and supply active power from the line in sympathy with the prevalent machine swings. The variable impedance type compensators can damp power oscillation only by modulated reactive compensation affecting the transmitted power.

Series reactive compensation can be highly effective in controlling power flow in the line and in improving the dynamic behavior of the power system. But certain problems related to the transmission angle cannot be handled by series compensation. For example, the prevailing transmission angle may not be compatible with the transmission requirements of a given line or it may vary with daily or seasonal system loads over too large a range to maintain acceptable power flow in some affected lines. To solve these problems, phase angle regulators (PAR) or phase shifting transformers (PST) are employed.

3 Combined Compensators

In the preceding sections shunt controllers and series controllers have been considered. They both have different influences on the line. In this section, the shunt and series compensator are compared first and then two compensators which are combinations of series and shunt controllers are discussed: the unified power flow controller and the interline power flow controller.

3.1 Comparison of Shunt and Series Compensators

The series-connected controllers impact the driving voltage and hence the current and power flow directly. Therefore, if the purpose of the application is to control the

current/power flow and damp oscillations, the series controllers are several times more powerful than the shunt controllers.

The shunt controllers are like current sources. They draw from or inject current into the line. Thus, shunt controllers are applied to control voltage at and around the point of connection through injection of reactive current. Because STATCOMs have the capability to inject active as well as reactive current they are able to provide an even more effective voltage control and damping of voltage oscillations.

This does not mean that the series controllers cannot be used for voltage control. Because the voltage fluctuations are largely a consequence of the voltage drop in series impedances of lines, transformers and generators, inserting a series compensator might be the most cost-effective way of improving the voltage profile. Nevertheless, a shunt controller is much more effective in maintaining a required voltage profile at a substation bus. That is because the shunt controller serves the bus node independently of the individual lines connected to the bus.

From the above consideration it can be followed that a combination of the series and shunt controllers can provide the best of both, i.e. an effective power/current flow and line voltage control.

3.2 Unified Power Flow Controller (UPFC)

Unified Power Flow Controller (UPFC): *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 active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent active 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 active and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation.*

The UPFC was developed for the real-time control and dynamic compensation of AC transmission systems. It is able to control all the parameters affecting power flow in the transmission line. Alternatively, it can independently control both the active and reactive power flow in the line.

The UPFC is conceptually a synchronous voltage source with controllable magnitude U_{pq} and angle ρ placed in series with the line (see Fig. 26). The voltage source exchanges both active and reactive power with the transmission system. But the voltage source can only produce reactive power, the active power has to be supplied to it by a power supply or a sink. This power supply is one of the end buses.

Presently, a UPFC consists of two voltage-source converters which are placed back-to-back and operated from a common DC link (DC storage capacitor). This implementation is shown in Fig. 27. The active power can freely flow in either direction between the AC terminals of the converters and each converter can generate or absorb reactive energy independently. Converter 2 injects the voltage \underline{U}_{pq} , which is controllable in magnitude and phase (ρ), in series with the line and therefore acts as the

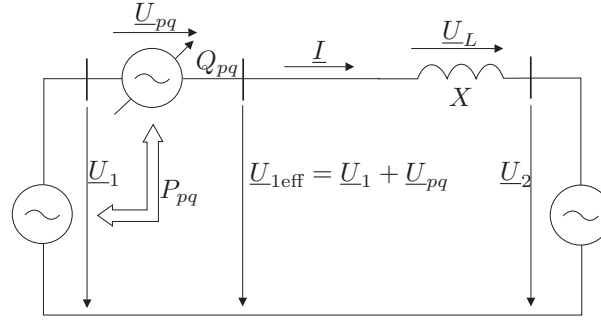


Figure 26: Concept of the UPFC in a two-machine power system

voltage source shown in Fig. 26. The reactive power exchanged at the AC terminal is generated by the converter internally. Opposed to this, the active power is converted into DC power which appears at the DC link as a positive or negative active power demand. This DC power demand is converted back to AC power by converter 1 and coupled to the transmission line bus via the supply transformer. Additionally, converter 1 can also exchange reactive power with the line, if necessary and provide independent shunt reactive compensation for the line.

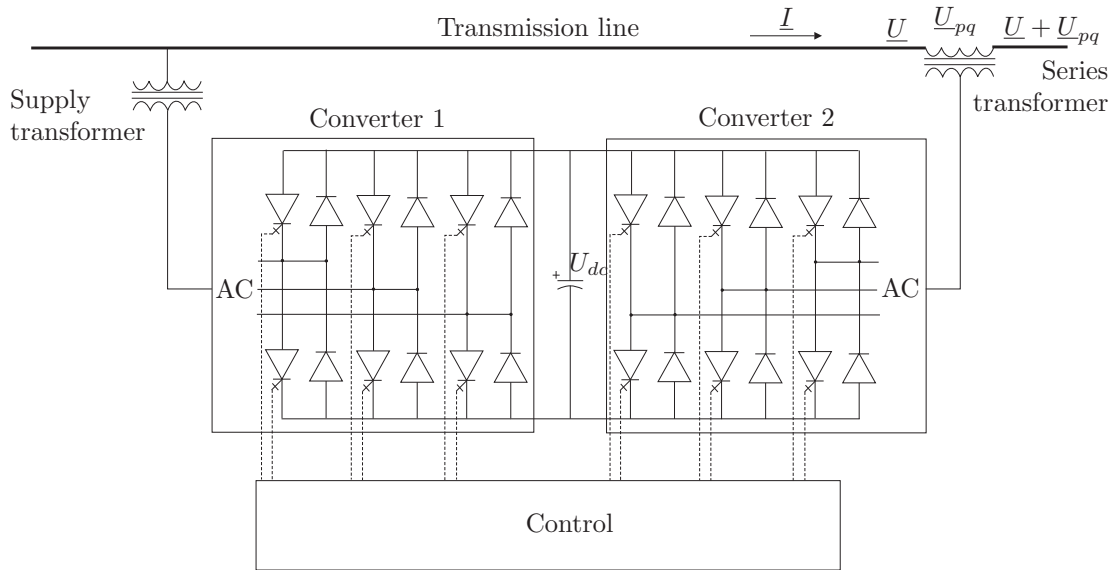


Figure 27: Implementation of a UPFC

For the system given in Fig. 28 a) the transmitted active power can be calculated as

$$P_1 = P_2 = P = \Re \{ \underline{U}_2 \cdot \underline{I}^* \} \quad (49)$$

With

$$\underline{I} = \frac{\underline{U}_{1\text{eff}} - \underline{U}_2}{jX} = \frac{\underline{U}_1 e^{j\delta} + \underline{U}_{pq} e^{j\rho} - \underline{U}_2}{jX} \quad (50)$$

(49) results in

$$P = \Re \left\{ U_2 \cdot \frac{U_1(\cos \delta - j \sin \delta) + U_{pq}(\cos \rho - j \sin \rho) - U_2}{-jX} \right\} \quad (51)$$

$$= \underbrace{\frac{U_1 U_2}{X} \sin \delta}_{P_0} + \underbrace{\frac{U_2 U_{pq}}{X} \sin \rho}_{\Delta P} \quad (52)$$

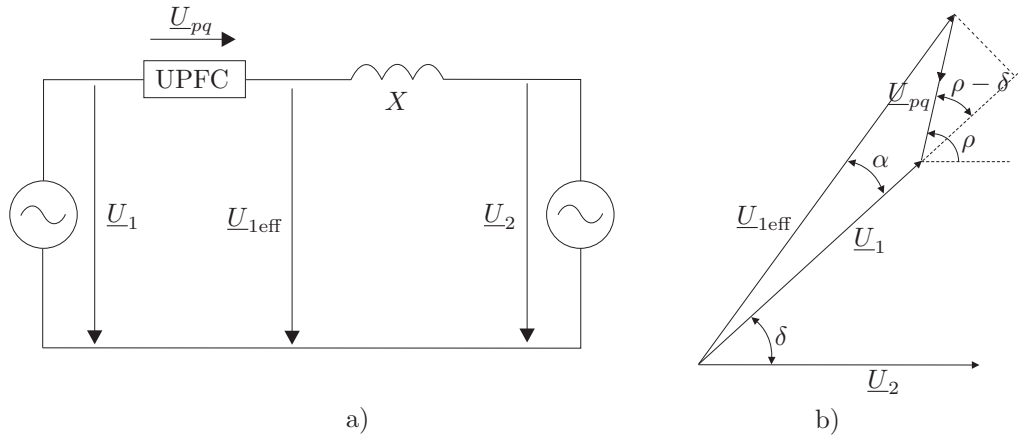


Figure 28: UPFC in two machine system

For a maximal influence of U_{pq} on the transmitted power, the angle ρ is equal to 90° . In Fig. 29, the corresponding transmitted power versus transmission angle characteristic is shown. Thus, the transmission characteristic is shifted up and down depending on the magnitude of the voltage of the UPFC.

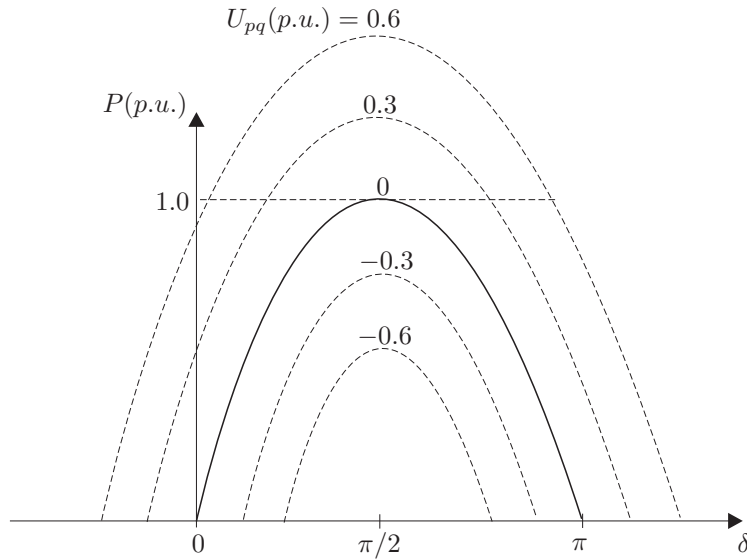


Figure 29: Transmitted power versus transmission angle for UPFC ($\rho = 90^\circ$)

The influence of a change in U_{pq} on the change of transmitted active power P at

different values of P , is

$$\frac{\partial P}{\partial U_{pq}} = \frac{U_2}{X} \sin \rho = \frac{P_0^{max}}{U_1} \sin \rho \quad (53)$$

where

$$P_0^{max} = \frac{U_1 U_2}{X}. \quad (54)$$

Thus, for constant P_0^{max} , U_1 and ρ , it is the same for all P . This can also be seen in Fig. 29 where the lines for different U_{pq} are equidistant.

The same considerations can be done for the angle ρ . The derivative of P with respect to ρ is

$$\frac{\partial P}{\partial \rho} = \frac{U_2 U_{pq}}{X} \cos \rho = P_0^{max} \frac{U_{pq}}{U_1} \cos \rho \quad (55)$$

Therefore, assuming that P_0^{max} , U_1 and U_{pq} are constant, also $\frac{\partial P}{\partial \rho}$ is the same for all P .

3.3 Interline Power Flow Controller (IPFC)

Interline Power Flow Controller (IPFC): *The combination of two or more Static Synchronous Series Compensators which are coupled via a common dc link to facilitate bi-directional flow of active power between the ac terminals of the SSSCs, and are controlled to provide independent reactive compensation for the adjustment of active 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 IPFC's common dc link, to provide shunt reactive compensation and supply or absorb the overall active power deficit of the combined SSSC's.*

The IPFC addresses the problem of compensating a number of transmission lines at a given substation. Series capacitive compensators are used to increase the transmittable active power over a given line but they are unable to control the reactive power flow in, and thus the proper load balancing of the line. With IPFC active power can be transferred between different lines. Therefore, it is possible to:

- equalize both active and reactive power flow between the lines,
- reduce the burden of overloaded lines by active 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.

The general form of a IPFC is shown in Fig. 30. It employs a number of DC-to-AC converters, namely SSSC, each providing series compensation for a different line.

With this scheme the converters do not only provide series reactive compensation but can also be controlled to supply active power to the common DC link from its own transmission line. Like this active power can be provided from the overloaded lines for active power compensation in other lines. This scheme requires a rigorous maintenance of the overall power balance at the common DC terminal by appropriate control action: the underloaded lines provide appropriate active power transfer for the overloaded lines.

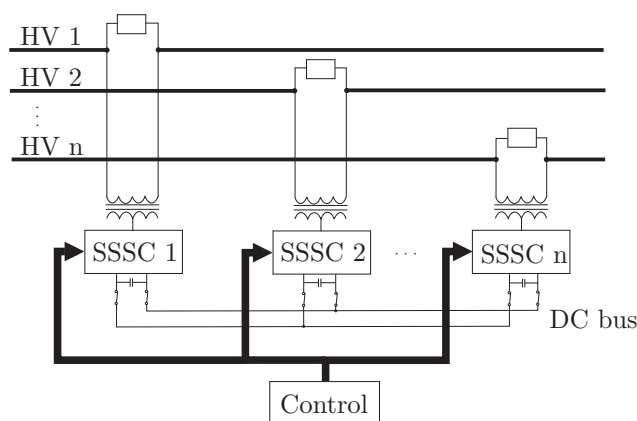


Figure 30: Interline Power Flow Controller

4 Use of FACTS

Shunt compensators, series compensators as well as combinations of these two types of compensators have been discussed. The application of these devices depends on the problem which has to be solved. In Table 4, an overview of problems occurring in the grid and which FACTS to be used to solve these problems are given.

Subject	Problem	Corrective action	FACTS
Voltage limits	Low voltage at heavy load	Supply reactive power	SVC, STAT-COM
		Reduce line reactance	TCSC
	High voltage at low load	Absorb reactive power	SVC, STAT-COM
	High voltage following an outage	Absorb reactive power, prevent overload	SVC, STAT-COM
	Low voltage following an outage	Supply reactive power, prevent overload	SVC, STAT-COM
Thermal limits	Transmission circuit overload	Increase transmission capacity	TCSC, SSSC, UPFC
Load flow	Power distribution on parallel lines	Adjust line reactances	TCSC, SSSC, UPFC
		Adjust phase angle	UPFC, SSSC, PAR
	Load flow reversal	Adjust phase angle	UPFC, SSSC, PAR
Short circuit power	High short circuit current	Limitation of short circuit current	TCSC, UPFC
Stability	Limited transmission power	Decrease line reactance	TCSC, SSSC

Table 1: Examples of use for FACTS

5 High-Voltage Direct-Current Transmission (HVDC)

Another option to control power flow is High-Voltage Direct-Current transmission (HVDC). HVDC devices convert AC to DC, transport it over a DC line and then convert DC back to AC. This has advantages over AC transmission in several applications [4]:

- Underwater cables: Cables have a large capacitance. For AC cables this results in a high charging current. If the cable is longer than about 50-60 kilometers the charging currents will fully load the cable and no real power transmission is possible. A solution to the problem would be to place shunt inductors every 50 kilometers. But to do so, land is required. DC cables do not have these drawbacks.
- AC system connection: To connect two AC systems of different frequencies, the power from one system can be converted to DC power, transported over the DC line and then fed into the other AC system with different frequency. Also, not synchronized networks can be connected like this.
- Long distance overhead transmission: If the transmission line is long (typically $\geq 600\text{km}$) the savings in line capital costs and losses with a DC line may countervail the investment costs for two converters and therefore a HVDC may be more favorable.

There are three categories of HVDC links

- Monopolar links (Fig. 31)
- Bipolar links (Fig. 32)
- Homopolar links (Fig. 33)

A monopolar link has only one conductor which is usually of negative polarity. The return path is provided by ground, water or, if the earth resistivity is too high or interference with underground metallic structures is possible, a metallic return may be used.

A bipolar link consists of two conductors, one of positive and one of negative polarity. Normally the currents in the two conductors are equal such that no ground current results. Nevertheless the two poles are independent of each other. Often there exist switches to bypass the converters in case a converter is faulted (dotted lines in Fig. 32). When such a fault is registered, these switches are shut and the faultless conductor can operate with this bypassed line. There would also be the possibility to operate with ground but mostly ground resistivity is very high or ground currents cannot be tolerated.

The homopolar link has two or more conductors. They all have the same polarity, usually negative because radio interference due to that the corona is then less intense. Ground is used as return path. In case of a faulted conductor, the converter is able to feed the other conductors which can carry more than normal power.

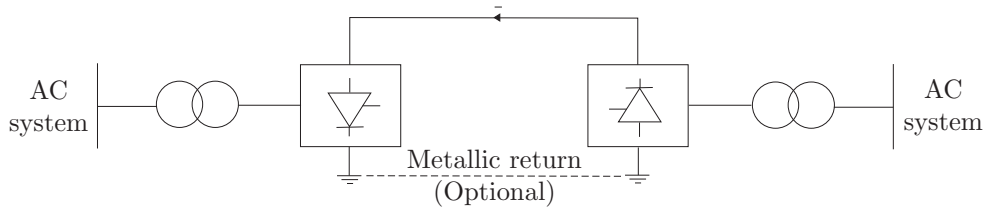


Figure 31: Monopolar HVDC link

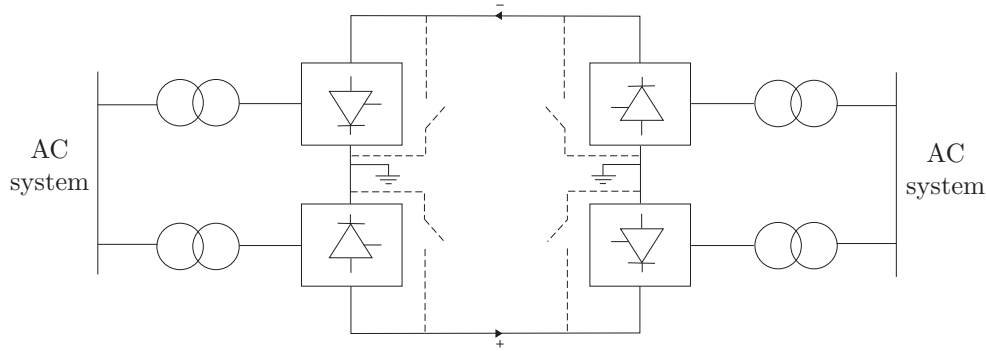


Figure 32: Bipolar HVDC link

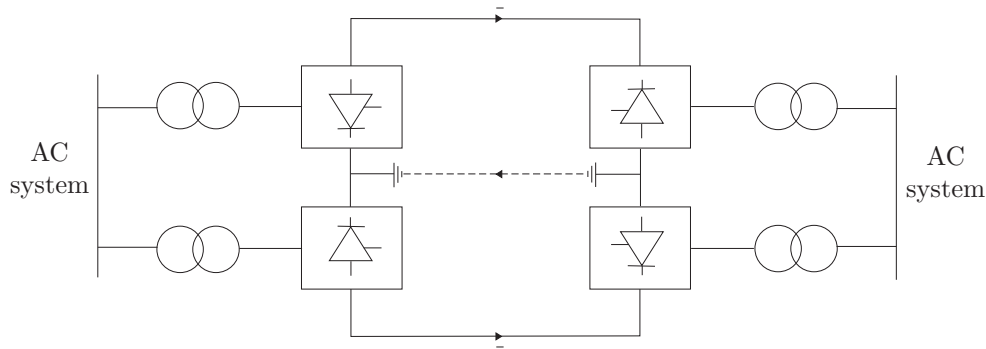


Figure 33: Homopolar HVDC link

The converters are a major part of the HVDC. They perform AC/DC conversion and provide the possibility to control the power flow through the HVDC link. The basic module of an HVDC converter is the three-phase, full-wave bridge circuit. In figure 34 such a circuit is given. The AC system, including the converter transformer is represented by ideal voltage sources

$$e_a = U_m \cos(\omega t + 60^\circ) \quad (56)$$

$$e_b = U_m \cos(\omega t - 60^\circ) \quad (57)$$

$$e_c = U_m \cos(\omega t - 180^\circ) \quad (58)$$

To simplify the considerations, the commutation reactances L_c are neglected. Therefore, commutation occurs instantaneously without overlap, i.e. no more than two valves conduct at any time. Another assumption is that the direct current i_d is constant which is justified because of the large smoothing reactor L_d .

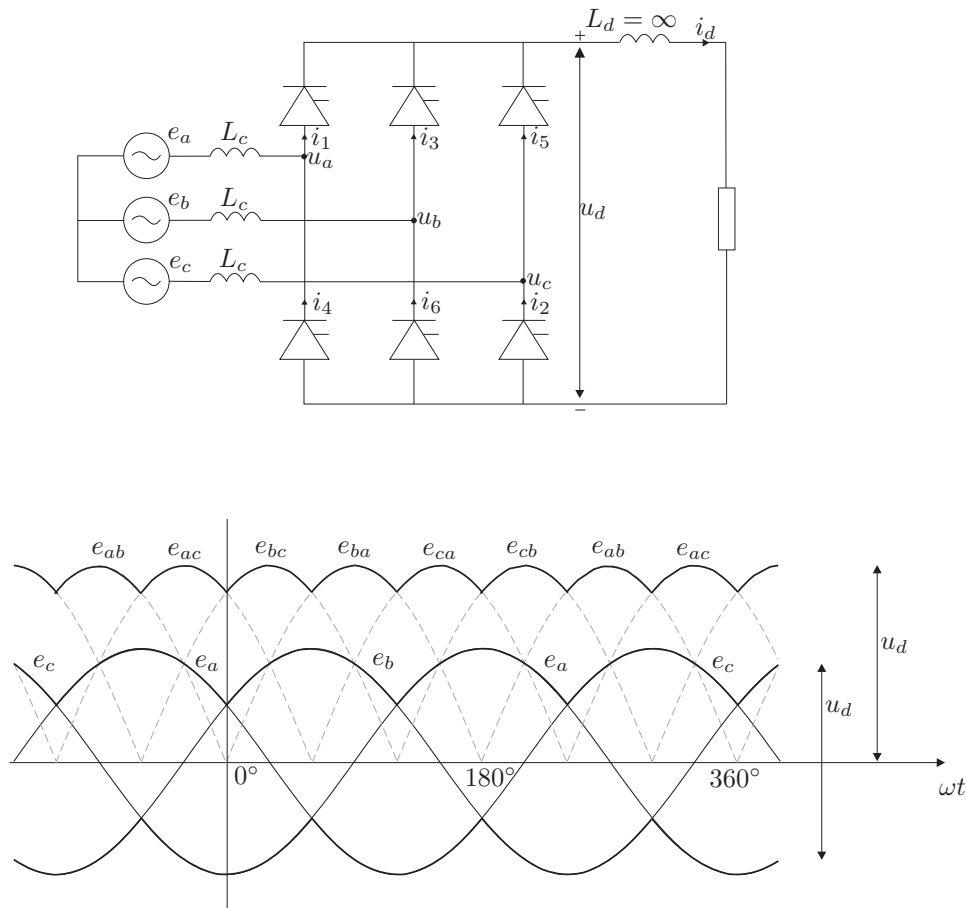


Figure 34: Circuit and waveforms for three-phase full-wave bridge converter

A valve conducts when the anode is at higher potential than the cathode and when a control pulse is applied to the gate. Considering the bridge in Fig. 34, always one valve of the upper row and one of the lower row is conducting. It depends on the phase-to-neutral voltages u_a , u_b and u_c and on the gate control, which valves these are. In the lower graph in Fig. 34, constant pulses are applied to all valves. If u_a is more positive than u_b and u_c , valve 1 conducts. The common potential of the valves in the upper row is then equal to that of the anode of valve 1 and therefore the valves 3 and 5 block. The considerations for the lower row is very similar. The valve whose corresponding phase-to-neutral voltage is more negative than the voltages of the other two valves conducts and determines the value of the common potential. Thus, the curve in the graph in Fig. 34 results for the voltage u_d .

The direct voltage u_d across the bridge is composed of 60° segments of the line-to-line voltages. Therefore, the average direct voltage U_{d0} is

$$U_{d0} = \frac{3}{\pi} \int_{-60^\circ}^{0^\circ} e_{ac} d\theta = 1.65 \cdot U_m \quad (59)$$

The gate control can be used to delay the ignition of the valves and therefore to control the voltage, respectively the power on the DC line (Fig. 35). With the firing

delay angle α the average direct voltage U_d is given as

$$U_d = U_{d0} \cos \cdot \alpha \quad (60)$$

α has to lie between 0° and 180° .

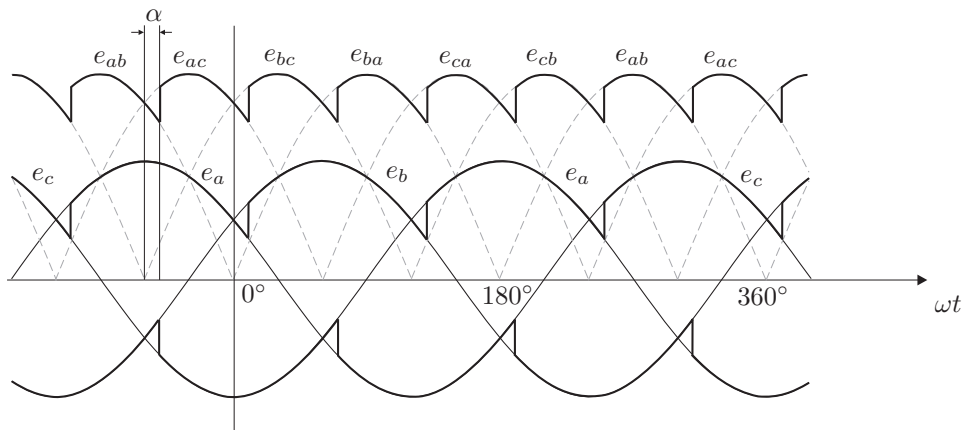


Figure 35: Waveforms for three-phase full-wave bridge converter with ignition delay

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