OBJECTIVES OF SHUNT COMPENSATION:

- Change the natural electrical characteristics of the transmission line to make it more compatible with the prevailing load demand.
- Thus, shunt connected, fixed or mechanically switched reactors are applied to minimize line overvoltage under light load conditions, and shunt connected, fixed or mechanically switched capacitors are applied to maintain voltage levels under heavy load conditions.
- The ultimate objective of applying reactive shunt compensation in a transmission system is to increase the transmittable power.

MIDPOINT VOLTAGE REGULATION FOR LINE SEGMENTATION:

- VAR compensation is thus used for voltage regulation at the midpoint (or some intermediate) to segment the transmission line and at the end of the (radial) line to prevent voltage instability, as well as for dynamic voltage control to increase transient stability and "damp power oscillations.

- Consider the simple two-machine (two-bus) transmission model in which an ideal var compensator is shunt connected at the midpoint of the transmission line. For simplicity, the line is represented by the series line inductance. The compensator is represented by a sinusoidal ac voltage source (of the fundamental frequency), in-phase with the midpoint voltage, \( V_m \) and with an amplitude identical to that of the sending and receiving-end voltages (\( V_m = V_s = V_r = V \)).

The midpoint compensator in effect segments the transmission line into two independent parts: The first segment, with an impedance of \( X/2 \), carries power from the sending end to the midpoint, and the second segment, also with an impedance of \( X/2 \), carries power from the midpoint to the receiving end.

The midpoint VAR compensator exchanges only reactive power with the transmission line in this process. For the lossless system assumed, the real power is the same at each terminal (sending end, midpoint, and receiving end) of the line.
The corresponding equations are

\[
V_s = V_m = V \cos \frac{\delta}{4} \\
I_s = I_m = I = \frac{4V}{X} \sin \frac{\delta}{4}
\]

The transmitted power is

\[
P = V_s I_s = V_m I_m = VI \cos \frac{\delta}{4} = \frac{2V^2}{X} \sin \frac{\delta}{2}
\]

\[
Q = V_s I_s = V_m I_m = VI \sin \frac{\delta}{4} = \frac{4V^2}{X} (1 - \cos \frac{\delta}{2})
\]

It can be observed that the midpoint shunt compensation can significantly increase the transmittable power (doubling its maximum value) at the expense of a rapidly increasing reactive power demand on the midpoint compensator (and also on the end-generators).

The midpoint of the transmission line is the best location for the compensator. This is because the voltage sag along the uncompensated transmission line is the largest at the midpoint. Also, the compensation at the midpoint breaks the transmission line into two equal segments for each of which the maximum transmittable power is the same. For unequal segments, the transmittable power of the longer segment would clearly determine the overall transmission limit. The same can be used for longer length of the lines.
END OF LINE VOLTAGE SUPPORT TO PREVENT VOLTAGE INSTABILITY:

A simple radial system with feeder line reactance of $X$ and load impedance $Z$, together with the normalized terminal voltage $V$, versus power $P$ plot at various load power factors, ranging from 0.8 lag and 0.9 lead.

The "nose-point" at each plot given for a specific power factor represents the voltage instability corresponding to that system condition. It should be noted that the voltage stability limit decreases with inductive loads and increases with capacitive loads. The shunt reactive compensation can effectively increase the voltage stability limit by supplying the reactive load and regulating the terminal voltage ($V - V_r = 0$).

It is evident that for a radial line, the end of the line, where the largest voltage variation is experienced, is the best location for the compensator. (Recall that, by contrast, the midpoint is the most effective location for the line interconnecting two ac system buses.)

Reactive shunt compensation is often used in practical applications to regulate the voltage at a given bus against load variations, or to provide voltage support for the load when, due to generation or line outages, the capacity of the sending-end system becomes impaired.

When a large load area is supplied from two or more generation plants with independent transmission lines. (This frequently happens when the locally generated power becomes inadequate to supply a growing load area and additional power is imported over a separate transmission link.) The loss of one of the power sources could suddenly increase the load demand on the remaining part of the system, causing severe voltage depression that could result in an ultimate voltage collapse.
Shunt compensation will be able to change the power flow in the system during and following dynamic disturbances so as to increase the transient stability limit and provide effective power oscillation damping.

The potential effectiveness of shunt (as well as other compensation and flow control techniques) on transient stability improvement can be conveniently evaluated by the EQUAL AREA CRITERION.

Assume that the complete system is characterized by the P versus δ curve "a" and is operating at angle δ holds to transmit power P when a fault occurs at line segment "1."
During the fault the system is characterized by the P versus δ curve "b" and thus, over this period, the transmitted electric power decreases significantly while mechanical input power to the sending-end generator remains substantially constant corresponding to $P_1$. As a result, the generator accelerates and the transmission angle increases from $\delta_1$ to $\delta_2$ at which the protective breakers disconnect the faulted line segment "1" and the sending-end generator 'absorbs accelerating energy, represented by area "$A_1$."

After fault clearing, without line segment "1" the degraded system is characterized by the P versus δ curve "c." At angle $\delta_2$ on curve "c" the transmitted power exceeds the mechanical input power $P_1$ and the sending end generator starts to decelerate; however, angle δ further increases due to the kinetic energy stored in the machine. The maximum angle reached at $\delta_3$, where the decelerating energy, represented by area "$A_2$, " becomes equal to the accelerating energy represented by area "$A_1". The limit of transient stability is reached at $\delta_3 = \delta_{\text{critical}}$, beyond which the decelerating energy would not balance the accelerating energy and synchronism between the sending end and receiving end could not be restored. The area "$A_{\text{margin}}", between $\delta_3$ and $\delta_{\text{critical}}$ represent the transient stability margin of the system.

From the above general discussion it is evident that the transient stability, at a given power transmission level and fault clearing time, is determined by the P versus δ characteristic of the post-fault system. Since appropriately controlled shunt compensation can provide effective voltage support, it can increase the transmission capability of the post-fault system and thereby enhance transient stability.
POWER OSCILLATION DAMPING:

- In the case of an under-damped power system, any minor disturbance can cause the machine angle to oscillate around its steady-state value at the natural frequency of the total electromechanical system.
- The angle oscillation, of course, results in a corresponding power oscillation around the steady-state power transmitted. The lack of sufficient damping can be a major problem in some power systems and, in some cases, it may be the limiting factor for the transmittable power.
- That is, when the rotationally oscillating generator accelerates and angle $\delta$ increases ($d\delta/dt>0$), the electric power transmitted must be increased to compensate for the excess mechanical input power. Conversely, when the generator decelerates and angle $\delta$ decreases ($d\delta/dt<0$), the electric power must be decreased to balance the insufficient mechanical input power. (The mechanical input power is assumed to be essentially constant in the time frame of an oscillation cycle.)

![Diagram of power oscillation damping](image)

SUMMARY OF COMPENSATOR REQUIREMENTS:

- The compensator must stay in synchronous operation with the AC system at the compensated bus under all operating conditions including major disturbances. Should the bus voltage be lost temporarily due to nearby faults, the compensator must be able to recapture synchronism immediately at fault clearing.
- The compensator must be able to regulate the bus voltage for voltage support and improved transient stability, or control it for power oscillation damping and transient stability enhancement, on a priority basis as system conditions may require.
- For a transmission line connecting two systems, the best location for Var compensation is in the middle, whereas for a radial feed to a load the best location is at the load end.
METHODS OF CONTROLLABLE VAR GENERATION:

- **VARIABLE IMPEDANCE TYPE STATIC VAR GENERATORS:**
  - THYRISTOR CONTROLLED / SWITCHED REACTOR (TCR/TSR)
  - THYRISTOR SWITCHED CAPACITOR (TSC)
  - FIXED CAPACITOR- THYRISTOR CONTROLLED REACTOR (FC-TCR).
  - THYRISTOR SWITCHED CAPACITOR-THYRISTOR CONTROLLED REACTOR

- **SWITCHING CONVERTER TYPE VAR GENERATORS:**
  - STATIC CONDENSOR & STATIC COMPENSTOR (STATCON & STATCOM)

- **HYBRID VAR GENERATORS:**
  - SWITCHING CONVERTER WITH TSC AND TCR

**THYRISTOR-CONTROLLED REACTOR (TCR):**

A basic single-phase Thyristor-Controlled Reactor (TCR) comprises an anti-parallel-connected pair of thyristor valves, T₁ and T₂, in series with a linear air-core reactor. The anti-parallel-connected thyristor pair acts like a bidirectional switch, with thyristor valve T₁ conducting in positive half-cycles and thyristor valve T₂ conducting in negative half-cycles of the supply voltage. The firing angle of the thyristors is measured from the zero crossing of the voltage appearing across its terminals.

The controllable range of the TCR firing angle, α extends from 90° to 180°. A firing angle of 90° results in full thyristor conduction with a continuous sinusoidal current flow in the TCR. As the firing angle is varied from 90° to close to 180°, the current flows in the form of discontinuous pulses symmetrically located in the positive and negative half-cycles.

Once the thyristor valves are fired, the cessation of current occurs at its natural zero crossing, a process known as the **Line Commutation**. The current reduces to zero for a firing angle of 180°. Thyristor firing at angles below 90° introduces dc components in the current, disturbing the symmetrical operation of the two anti-parallel valve branches.

A characteristic of the line-commutation process with which the TCR operates is that once the valve conduction has commenced, any change in the firing angle can only be implemented in the next half-cycle, leading to the so-called thyristor dead time.
FOR FIRING ANGLE $\alpha = 90^\circ$

FOR FIRING ANGLE $\alpha = 105^\circ$
FOR FIRING ANGLE $\alpha = 150^\circ$

Let the source voltage is

$$V_s(t) = V \sin \omega t$$

Where $V$= peak voltage of the applied voltage and $\omega$ = Angular Frequency

The TCR current is given by

$$L \frac{di}{dt} - V_s(t) = 0$$

where $L$ is the inductance of the TCR

$$i(t) = \frac{1}{L} \int V_s(t) dt + C$$

Where $C$ is integration constant

$$i(t) = -\frac{V}{\omega L} \cos \omega t + C$$

For finding $C$ use initial conditions $i(\omega t = \alpha) = i(t) = 0$

$$i(t) = -\frac{V}{\omega L} (\cos \alpha - \cos \omega t)$$
Where $\alpha$ is the firing angle measured from positive going zero crossing of the applied voltage.

Fourier analysis is used to derive the fundamental component of the TCR current $I_1(\alpha)$, which, in general, is given as

$$I_1(\alpha) = a_1 \cos \omega t + b_1 \sin \omega t$$

Where $b_1 = 0$ because of the odd symmetry, that is, $f(x) = f(-x)$. Also, no even harmonics are generated because of the half-wave symmetry, that is,

$$F(x + T/2) = -f(x)$$

The coefficient

$$a_1 = \frac{4}{\pi} \int_0^{T/2} f(x) \cos \frac{2\pi}{T} \, \, dx$$

$$I_1(\alpha) = \frac{V}{\omega L} \left( 1 - \frac{2\alpha}{\pi} - \frac{1}{\pi} \sin 2\alpha \right)$$

$$I_1(\alpha) = VB_T(\alpha)$$

Where

$$B_T(\alpha) = B_{in} \left( 1 - \frac{2\alpha}{\pi} - \frac{1}{\pi} \sin 2\alpha \right)$$

$$B_{max} = 1/\omega L$$

The firing angle $\alpha$ is related to the conduction angle $\sigma$, as follows:

$$\sigma + \frac{\alpha}{2} = \pi$$

$$I_1(\sigma) = VB_{in} \left( \frac{\sigma - \sin \sigma}{\pi} \right)$$

$$I_1(\sigma) = VB_T(\sigma)$$

$$B_T(\sigma) = B_{in} \left( \frac{\sigma - \sin \sigma}{\pi} \right)$$
The TCR thus acts like a variable susceptance. Variation of the firing angle changes the susceptance and, consequently, the fundamental-current component, which leads to a variation of reactive power absorbed by the reactor because the applied ac voltage is constant. However, as the firing angle is increased beyond 90°, the current becomes non-sinusoidal, and harmonics are generated. If the two thyristors are fired symmetrically in the positive and negative half-cycles, then only odd-order harmonics are produced.

The harmonics can be deduced through a Fourier analysis of higher-frequency components. The rms value of the nth-order harmonic is expressed as a function of $\alpha$ in the following equation

$$I_{n}(\alpha) = \frac{V}{\omega n} \left\{ \sum_{k=1}^{\infty} \frac{1}{n+1} \sin (\alpha(n+1)) - \sin (\alpha n) \right\}$$

Where $n = 2K+1$ and $K = 1, 2, 3, \ldots$
THYRISTOR-SWITCHED REACTOR:

- The TSR is a special case of a TCR in which the variable firing-angle control option is not exercised. Instead, the device is operated in two states only: either fully on or fully off.

- If the thyristor valves are fired exactly at the voltage peaks corresponding to $\alpha = 90^\circ$ for the forward-thyristor valve $T_1$ and $\alpha = 270^\circ$ ($90 + 180$) for the reverse-thyristor valve $T_2$. The maximum inductive current flows in the TCR as if the thyristor switches were replaced by short circuits. However, if no firing pulses are issued to the thyristors, the TSR will remain in a blocked-off state, and no current can flow.

- The TSR ensures a very rapid availability of rated inductive reactive power to the system. When a large magnitude of controlled reactive power, $Q$, is required, a part of $Q$ is usually assigned to a small TSR of rating, say, $Q/2$; the rest is realized by means of a TCR also of a reduced rating $Q/2$. This arrangement results in substantially decreased losses and harmonic content as compared to a single TCR of rating $Q$.

THYRISTOR-SWITCHED CAPACITOR (TSC):

The circuit consists of a capacitor in series with a bidirectional thyristor switch. It is supplied from an ideal ac voltage source with neither resistance nor reactance present in the circuit.

The analysis of the current transients after closing the switch brings forth two cases:

SWITCHING A CAPACITOR TO A VOLTAGE SOURCE:

**Case-1:** The capacitor voltage is not equal to the supply voltage when the thyristors are fired. Immediately after closing the switch, a current of infinite magnitude flows and charges the capacitor to the supply voltage in an infinitely short time. The switch realized by thyristors cannot withstand this stress and would fail.

**Case-2:** The capacitor voltage is equal to the supply voltage when the thyristors are fired, the analysis shows that the current will jump immediately to the value of the steady-state current. The steady state condition is reached in an infinitely short time. Although the magnitude of the current does not exceed the steady-state values, the thyristors have an upper limit of $di/dt$ values that they can withstand during the firing process. Here, $di/dt$ is infinite, and the thyristor switch will again fail.
Switching a Series Connection of a Capacitor and Reactor:

To overcome the problems discussed in the preceding list, a small damping reactor is added in series with the capacitor.

Let the source voltage be

\[ V_s(t) = V \sin \omega_0 t \]

Where \( \omega_0 \) is the system nominal frequency.

The analysis of the current after closing the thyristor switch at \( t = 0 \) leads to the following results

\[ i(t) = I_A \cos (\omega_0 t + \alpha) - nB_L \left( V_{C0} - \frac{n^2}{n^2 - 1} V \sin \alpha \right) \sin \omega_n t - I_A \cos \alpha \cos \omega_n t \]

where the natural frequency is

\[ \omega_n = n\omega_c = \frac{1}{\sqrt{LC}} = \frac{X_L}{\sqrt{X_L}} \]

\[ I_A = \sqrt{\frac{B_L B_C}{B_L + B_C}} \]

Here, \( V_{C0} \) is initial capacitor voltage at \( t = 0 \). It is well-worth discussing this result in some detail. Note that no damping is considered in the circuit.
The Term Involving Fundamental Frequency ($\omega_0$):

This term represents the steady-state solution. As expected, the current leads the voltage by $90^\circ$. The current magnitude, $I_{AC}$, as obtained in the foregoing equation, can be alternatively expressed as

$$I_A = VB_L \left[ \frac{n^2}{n^2 - 1} \right]$$

A magnification in current by a factor of $n^2 / (n^2 - 1)$ is seen as compared to the case without reactor. The same magnification factor is also inherent in the magnitude of the capacitor voltage.

![Diagram showing the relationship between n and the current magnitude](image)

Voltage across the capacitor (peak) is

$$V_L = IX_L = V \left[ \frac{n^2}{n^2 - 1} \right]$$

The TSC branch can be disconnected ("switched out") at any current zero by prior removal of the gate drive to the thyristor valve. At the current zero crossing, the capacitor voltage is at its peak value. The disconnected capacitor stays charged to this voltage and, consequently, the voltage across the nonconducting thyristor valve varies between zero and the peak-to-peak value of the applied ac voltage.

If the voltage across the disconnected capacitor remained unchanged, the TSC bank could be switched in again, without any transient, at the appropriate peak of the applied ac voltage.

Normally, the capacitor bank is discharged after disconnection. Thus, the reconnection of the capacitor may have to be executed at some residual capacitor voltage between zero and $V n^2/(n^2 - 1)$. This can be accomplished with the minimum possible transient disturbance if the thyristor valve is turned on at those instants at which the capacitor residual voltage and the applied ac voltage are equal, that is, when the voltage across the thyristor valve is zero.

These transients are caused by the nonzero $dv/dt$ at the instant of switching, which, without the series reactor, would result in an instantaneous current of $I_C = Cdv/dt$ in the capacitor. (This current represents the instantaneous value of the steady-state capacitor current at the time of the switching.)

The interaction between the capacitor and the current (and $di/dt$) limiting reactor, with the damping resistor, produces the oscillatory transients visible on the current and
voltage waveforms. (Note that the switching transient is greater for the fully discharged than for the partially discharged capacitor because the $dv/dt$ of the applied (sinusoidal) voltage has its maximum at the zero crossing point.

**Case-1**: If the residual capacitor voltage is lower than the peak ac voltage ($V_c < V$), then the correct instant of switching is when the instantaneous ac voltage becomes equal to the capacitor voltage.

**Case-2**: If the residual capacitor voltage is equal to or higher than the peak ac voltage ($V_c \geq V$), then the correct switching is at the peak of the ac voltage at which the thyristor valve voltage is minimum.
FIXED CAPACITOR, THYRISTOR-CONTROLLED REACTOR (FC-TCR):

A basic var generator arrangement using a fixed (permanently connected) capacitor with a thyristor-controlled reactor (FC-TCR). The current in the reactor is varied by the previously discussed method of firing delay angle control.

The fixed capacitor in practice is usually substituted, fully or partially, by a filter network that has the necessary capacitive impedance at the fundamental frequency to generate the reactive power required, but it provides low impedance at selected frequencies to shunt the dominant harmonics produced by the TCR.

The fixed capacitor, thyristor-controlled reactor type var generator may be considered essentially to consist of a variable reactor (controlled by delay angle $\alpha$) and a fixed capacitor.

As seen, the constant capacitive var generation $(Q_c)$ of the fixed capacitor is opposed by the variable var absorption $(Q_L)$ of the thyristor-controlled reactor, to yield the total var output $(Q)$ required.

At the maximum capacitive var output, the thyristor-controlled reactor is off $(\alpha = 90^\circ)$. To decrease the capacitive output, the current in the reactor is increased by decreasing delay angle $\alpha$. At zero var output, the capacitive and inductive currents become equal and thus the capacitive and inductive vars cancel out. With a further decrease of angle $\alpha$ (assuming that the rating of the reactor is greater than that of the capacitor), the inductive current becomes larger than the capacitive current, resulting in a net inductive var output.

At zero delay angle, the thyristor-controlled reactor conducts current over the full 180 degree interval, resulting in maximum inductive var output that is equal to the difference between the vars generated by the capacitor and those absorbed by the fully conducting reactor.
CONTROL OF THE THYRISTOR-CONTROLLED REACTOR IN THE FC-TCR:

One function is synchronous timing. This function is usually provided by a phase locked loop circuit that runs in synchronism with the ac system voltage and generates appropriate timing pulses with respect to the peak of that voltage.

In a different approach, the ac voltage itself may be used for timing. However, this seemingly simple approach presents difficult problems during system faults and major disturbances when the voltage exhibits wild fluctuations and large distortion.

The second function is the reactive current (or admittance) to firing angle conversion. This can be provided by a real time circuit implementation of the mathematical relationship between the amplitude of the fundamental TCR current $I_{LF}(\alpha)$ and the delay angle $\alpha$. Several circuit approaches are possible. One is an analog function generator producing in each half-cycle a scaled electrical signal that represents the $I_{LF}(\alpha)$ versus a relationship.

An other is a digital "look-up table" for the normalized $I_{LF}(\alpha)$ versus $\alpha$ function which is read at regular intervals (e.g., at each degree) starting from $\alpha = 0$ (peak of the voltage) until the requested value is found, at which instant a firing pulse is initiated.

A third approach is to use a microprocessor and compute, prior to the earliest firing Angle ($\alpha = 0$), the delay angle corresponding to the required $I_{LF}(\alpha)$ . The actual firing instant is then determined simply by a timing circuit (e.g., a counter) "measuring" $\alpha$ from the peak of the voltage.

The third function is the computation of the required fundamental reactor current $I_{LF}$ from the requested total output current $I_Q$ (sum of the fixed capacitor and the TCR
currents) defined by the amplitude reference input $I_{QRef}$ to the var generator control. This is simply done by subtracting the (scaled) amplitude of the capacitor current, $I_C$ from $I_{QRef}$ (Positive polarity for $I_{QRef}$ means inductive output current, and negative polarity means capacitive output current.).

The fourth function is the thyristor firing pulse generation. This is accomplished by the firing pulse generator (or gate drive) circuit which produces the necessary gate current pulse for the thyristors to turn on in response to the output signal provided by the reactive current to firing angle converter. The gate drive circuits are sometimes at ground potential with magnetic coupling to the thyristor gates; more often, however, they are at the (high) potential level of the thyristors. In the latter case, in order to provide sufficient insulation between the ground level control and the gate drive circuits, the gating information is usually transmitted via optical fibers ("light pipes").
The V-I operating area of the FC-TCR var generator is defined by the maximum attainable capacitive and inductive admittances and by the voltage and current ratings of the major power components (capacitor, reactor, and thyristor valve). The ratings of the power components are derived from application requirements.

The dynamic performance (e.g., the frequency band) of the var generator is limited by the firing angle delay control, which results in a time lag or transport lag with respect to the input reference signal. The actual transfer function of the FC-TCR type var generator can be expressed with the transport lag in the following form:

\[ G(S) = Ke^{-T_d \alpha} \]

Where \( S \) is Laplace operator, \( K \) is gain constant, \( T_d \) is time lag and firing angle \( \alpha \)

**THYRISTOR-SWITCHED CAPACITOR-THYRISTOR-CONTROLLED REACTOR (TSC-TSR):**

A basic single-phase TSC-TCR arrangement is shown. For a given capacitive output range, it typically consists of \( n \) TSC branches and one TCR. The number of branches \( n \) is determined by practical considerations that include the operating voltage level, maximum var output, current rating of the thyristor valves, bus work and installation cost, etc. Of course, the inductive range also can be expanded to any maximum rating by employing additional TCR branches.

The total capacitive output range is divided into \( n \) intervals. In the first interval, the output of the var generator is controllable in the zero to \( Q_{c_{\text{max}}}/n \) range, where \( Q_{c_{\text{max}}} \) is the total rating provided by all TSC branches.

In this interval, one capacitor bank is switched in (by firing, for example, thyristor valve \( S_{W1} \)) and, simultaneously, the current in the TCR is set by the appropriate firing delay angle so that the sum of the var output of the TSC (negative) and that of the TCR (positive) equals the capacitive output required.
In the second, third, ..., and nth intervals, the output is controllable in the $Q_{c_{\text{max}}}/n$ to $2Q_{c_{\text{max}}}/n$, $2Q_{c_{\text{max}}}/n$ to $3Q_{c_{\text{max}}}/n$, ..., and $(n - 1)Q_{c_{\text{max}}}/n$ to $Q_{c_{\text{max}}}$ range by switching in the second, third, ..., and nth capacitor bank and using the TCR to absorb the surplus capacitive vars.

By being able to switch the capacitor banks in and out within one cycle of the applied ac voltage, the maximum surplus capacitive var in the total output range can be restricted to that produced by one capacitor bank, and thus, theoretically, the TCR should have the same var rating as the TSC. However, to ensure that the switching conditions at the endpoints of the intervals are not indeterminate, the var rating of the TCR has to be somewhat larger in practice than that of one TSC in order to provide enough overlap (hysteresis) between the "switching in" and "switching out" var levels.

As seen, the capacitive var output, $Q_C$, is changed in a step-like manner by the TSC’s to approximate the var demand with a net capacitive var surplus, and the relatively small inductive var output of the TCR, $Q_L$, is used to cancel the surplus capacitive vars.

A functional control scheme for the TSC-TCR type var generator. It provides three major functions:
1. Determines the number of TSC branches needed to be switched in to approximate the required capacitive output current (with a positive surplus), and computes the amplitude of the inductive current needed to cancel the surplus capacitive current.
2. Controls the switching of the TSC branches in a "transient-free" manner.
3. Varies the current in the TCR by firing delay angle control.
The input current reference $I_{\text{QRef}}$ representing the magnitude of the requested output current is divided by the (scaled) amplitude $I_C$ of the current that a TSC branch would draw at the given amplitude $V$ of the ac voltage. The result, rounded to the next higher integer, gives the number of capacitor banks needed. The difference in magnitude between the sum of the activated capacitor currents, $\sum I_C$ and the reference current, $I_{\text{QRef}}$ gives the amplitude, $I_{\text{LF}}$ of the fundamental reactor current required.

The basic logic for the second function (switching of the TSC branches). This follows the two simple rules for "transient-free" switching. That is, either switch the capacitor bank when the voltage across the thyristor valve becomes zero or when the thyristor valve voltage is at a minimum. (The first condition can be met if the capacitor residual voltage is less than the peak ac voltage and the latter condition is satisfied at those peaks of the ac voltage which has the same polarity as the residual voltage of the capacitor.)

The actual firing pulse generation for the thyristors in the TSC valve is similar to that used for the TCR with the exception that a continuous gate drive is usually provided to maintain continuity in conduction when the current is transferred from one thyristor string carrying current of one polarity (e.g., positive) to the other string carrying current of opposite polarity (e.g., negative).

The third function (TCR firing delay angle control) is identical to that used in the fixed-capacitor, thyristor-controlled reactor scheme. The reactive current reference signal $I_{\text{QRef}}$, the total output current $i_Q$, the current $i_C = I_C + I_L$ drawn by the thyristor switched capacitor banks, and the current $i_L$ drawn by the thyristor-controlled reactor.
TSC turns on if: 

- "on" = 1 and $V_{SW} = 1$ 
- or 
- "on" = 1 and $P_r = 1$ and $V_{SW} = 1$

- $V_{SW} = 1$ when $V_C = V$
- $P_r = 1$ when $V = V$
- $V_{SW} = 1$ when sign $V$ = sign $V_C$

Var demand (lag to lead)

$$i = i_C + i_L$$

$V_L$  

$V_{max}$ is voltage limit for TSC

$V_{Lmax}$ is voltage limit for TCR

$I_C$ is capacitive current limit

$I_{Lmax}$ is inductive current limit

$B_{Lmax}$ is max admittance of TCR

$B_C$ is admittance of TSC

$B_{Cmax}$ is max capacitive admittance
SWITCHING CONVERTER TYPE VAR GENERATORS:

Static var generators discussed in the previous section generate or absorb controllable reactive power (var) by synchronously switching capacitor and reactor banks "in" and "out" of the network.

The aim of this approach is to produce a variable reactive shunt impedance that can be adjusted (continuously or in a step-like manner) to meet the compensation requirements of the transmission network. The possibility of generating controllable reactive power directly, without the use of ac capacitors or reactors, by various switching power converters was disclosed by Gyugyi in 1976.

These (dc to ac or ac to ac) converters are operated as voltage and current sources and they produce reactive power essentially without reactive energy storage components by circulating alternating current among the phases of the ac system.

Synchronous machine whose reactive power output is varied by excitation control. Like the mechanically powered machine, they can also exchange real power with the ac system if supplied from an appropriate, usually dc energy source. Because of these similarities with a rotating synchronous generator, they are termed Static Synchronous Generators (SSGs). When an SSG is operated without an energy source, and with appropriate controls to function as a shunt-connected reactive compensator, it is termed, analogously to the rotating Synchronous Compensator (condenser), a Static Synchronous Compensator (Condenser) STATCOM STATCON.

BASIC OPERATING PRINCIPLES:

The basic principle of reactive power generation by a voltage-sourced converter is akin to that of the conventional rotating synchronous machine. For purely reactive power flow, the three-phase induced electromotive forces (EMF’s) $E_a$, $E_b$ and $E_c$ of the synchronous rotating machine are in phase with the system voltages, $V_a$, $V_b$, and $V_c$. The reactive current $I$ drawn by the synchronous compensator is determined by the magnitude of the system voltage $V$, that of the internal voltage $E$, and the total circuit reactance (synchronous machine reactance plus transformer leakage reactance plus system short circuit reactance $X$).

$$I = \frac{V - E}{X}$$

The corresponding reactive power $Q$ exchanged can be expressed as follows

$$Q = \frac{1 - E}{X} V^2$$
By controlling the excitation of the machine, and hence the amplitude $E$ of its internal voltage relative to the amplitude $V$ of the system voltage, the reactive power flow can be controlled. Increasing $E$ above $V$ (i.e., operating over-excited) results in a leading current, that is, the machine is "seen" as a capacitor by the ac system.

Decreasing $E$ below $V$ (i.e., operating under-excited) produces a lagging current, that is, the machine is "seen" as a reactor (inductor) by the ac system. Under either operating condition a small amount of real power of course flows from the ac system to the machine to supply its mechanical and electrical losses.

Note that if the excitation of the machine is controlled so that the corresponding reactive output maintains or varies a specific parameter of the ac system (e.g., bus voltage), then the machine (rotating var generator) functions as a rotating synchronous compensator (condenser).

The basic voltage-sourced converter scheme for reactive power generation is shown in the form of a single-line diagram. From a dc input voltage source, provided by the charged capacitor $C$, the converter produces a set of controllable three-phase output voltages with the frequency of the ac power system. Each output voltage is in phase with, and coupled to the corresponding ac system voltage via a relatively small (0.1-0.15 p.u.) tie reactance (which in practice is provided by the per phase leakage inductance of the coupling transformer).

By varying the amplitude of the output voltages produced, the reactive power exchange between the converter and the ac system can be controlled in a manner similar to that of the rotating synchronous machine. That is, if the amplitude of the output voltage is increased above that of the ac system voltage, then the current flows through the tie reactance from the converter to the ac system, and the converter generates reactive (capacitive) power for the ac system.

If the amplitude of the output voltage is decreased below that of the ac system, then the reactive current flows from the ac system to the converter, and the converter absorbs reactive (inductive) power. If the amplitude of the output voltage is equal to that of the ac system voltage, the reactive power exchange is zero.
Since the converter supplies only reactive output power (its output voltages are controlled to be in phase with the ac system voltages), the real input power provided by the dc source (charged capacitor) must be zero (as the total instantaneous power on the ac side is also zero).

Furthermore, since reactive power at zero frequency (at the dc capacitor) by definition is zero, the dc capacitor plays no part in the reactive power generation. In other words, the converter simply interconnects the three ac terminals in such a way that the reactive output currents can flow freely between them. Viewing this from the terminals of the ac system, one could say that the converter establishes a circulating current flow among the phases with zero net instantaneous power exchange.

**BASIC CONTROL APPROACHES:**

A static (var) generator converter comprises a large number of gate controlled semiconductor power switches (GTO thyristors). The gating commands for these devices are generated by the internal converter control (which is part of the var generator proper) in response to the demand for reactive and/or real power reference signal(s).

The reference signals are provided by the external or system control, from operator instructions and system variables, which determine the functional operation of the STATCOM.

The internal control is an integral part of the converter. Its main function is to operate the converter power switches so as to generate a fundamental output voltage waveform with the demanded magnitude and phase angle in synchronism with the ac system. In this way the power converter with the internal control can be viewed as a sinusoidal, synchronous voltage source behind a tie reactor (provided by the leakage inductance of the coupling transformer), the amplitude and phase angle of which are controlled by the external (STATCOM system) control via appropriate reference signal(s).

The main function of the internal control, as stated above, is to operate the converter power switches so as to produce a synchronous output voltage waveform that forces the reactive (and real) power exchange required for compensation.

The internal control achieves this by computing the magnitude and phase angle of the required output voltage from \( I_{Q\text{Ref}} \) and \( I_{P\text{Ref}} \) provided by the external control and generating a set of coordinated timing waveforms ("gating pattern"), which determines the on and off periods of each switch in the converter corresponding to the wanted output voltage. These timing waveforms have a defined phase relationship between them, determined by the converter pulse number, the method used for constructing the output voltage waveform, and the required angular phase relationship between the three outputs (normally 120 degrees).

The magnitude and angle of the output voltage are those internal parameters which determine the real and reactive current the converter draws from, and thereby the real and reactive power it exchanges with the ac system.

If the converter is restricted for reactive power exchange, i.e., it is strictly operated as a static var generator, then the reference input to the internal control is the required reactive current. From this the internal control derives the necessary magnitude and angle
for the converter output voltage to establish the required dc voltage on the dc capacitor since the magnitude of the ac output voltage is directly proportional to the dc capacitor voltage. Because of this proportionality, the reactive output current, as one approach, can be controlled indirectly via controlling the dc capacitor voltage (which in turn is controlled by the angle of the output voltage) or, as another approach, directly by the internal voltage control mechanism (e.g., PWM) of the converter in which case the dc voltage is kept constant (by the control of the angle).

There are two basic approaches to output voltage, and thus to var control

1. Indirect output voltage control
2. Direct” output voltage control

**Block diagram of the internal control for purely reactive compensation, based on the indirect approach of dc capacitor voltage control:**

The inputs to the internal control are: the ac system bus voltage \( v \), the output current of the converter \( i_0 \) reference, and the reactive current \( I_{QRef} \). Voltage \( v \) operates a phase-locked loop that provides the basic synchronizing signal, angle \( \theta \).

The output current, \( i_0 \)’, is decomposed into its reactive and real components, and the magnitude of the reactive current component, \( I_{0Q} \) to the reactive current reference, \( I_{QRef} \) is compared. The error thus obtained provides, after suitable amplification, angle \( \alpha \), which defines the necessary phase shift between the output voltage of the converter and the ac system voltage needed for charging (or discharging) the storage capacitor to the dc voltage level required.

Accordingly, angle \( \alpha \) is summed to \( \theta \) to provide angle \( \theta + \alpha \), which represents the desired synchronizing signal for the converter to satisfy the reactive current reference. Angle \( \theta + \alpha \) operates the gate pattern logic (which may be a digital look-up table) that provides the individual gate drive logic signals to operate the converter power switches.

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\[ i_0 = I_{OP} + I_{OQ} \]

\[ v_o = V_o / \alpha \]

\[ v; (V/0°) \]
Block diagram of the internal control for a converter with direct internal voltage control capability, such as the three-level converter:

The input signals are again the bus voltage, $v$, the converter output current, $i_0$, and the reactive current reference, $I_{Q\text{Ref}}$, plus the dc voltage reference $V_{dc}$. This dc voltage reference determines the real power the converter must absorb from the ac system in order to supply its internal losses.

The converter output current is decomposed into reactive and real current components. These components are compared to the external reactive current reference (determined from compensation requirements) and the internal real current reference derived from the dc voltage regulation loop. After suitable amplification, the real and reactive current error signals are converted into the magnitude and angle of the wanted converter output voltage, from which the appropriate gate drive signals, in proper relationship with the phase-locked loop provided phase reference, are derived.
Note that this internal control scheme could operate the converter with a dc power supply or energy storage as a static synchronous generator. In this case the internal real current reference would be summed to an externally provided real current reference that would indicate the desired real power exchange (either positive or negative) with the ac system. The combined internal and external real current references (for converter losses and active power compensation), together with the prevailing reactive current demand, would determine the magnitude and angle of the output voltage generated, and thus the real and reactive power exchanged with the ac system.
HYBRID VAR GENERATORS: SWITCHING CONVERTER WITH TSC AND TCR:

The converter-based var generator can generate or absorb the same amount of maximum reactive power; in other words, it has the same control range for capacitive and inductive var output. However, many applications may call for a different var generation and absorption range. This can simply be achieved by combining the converter with either fixed and/or thyristor-switched capacitors and/or reactors.