This reactor is needed primarily to limit the surge current in the thyristor switch & it may also be used to avoid resonances with the AC system impedance at perticular Frequencies.

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

TSC is a subset of SVC in which thyristor based AC switches are used to switch in & out (without firing control) shunt capacitor units, in order to achieve the required step change in the reactive power supplied to the system.

Under steady state condition, when the thyristor switch is closed & the TSC branch is connected to a sinusoidal AC voltage source, $v = V \sin \omega t$. Then required capacitive current will flow to the system. The current in the branch is given by,

$$i(\omega t) = V \frac{n^2}{n^2-1} \omega C \cos \omega t \quad \text{--- (1)}$$

where, $n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_C}{X_L}}$ = resonant frequency --- (2)

The amplitude of the voltage across the capacitor is,

$$V_C = \frac{n^2}{n^2-1} V \quad \text{--- (3)}$$

TSC branch can be disconnected ("switched out") at any current zero by prior removal pulse for the thyristor switch.

At the current zero crossing, the capacitor voltage is at its peak value. The disconnected capacitor stays charged to this voltage.

Consequently, the voltage across the non-conducting thyristor switch varies between zero & peak-to-peak value of the applied AC voltage.

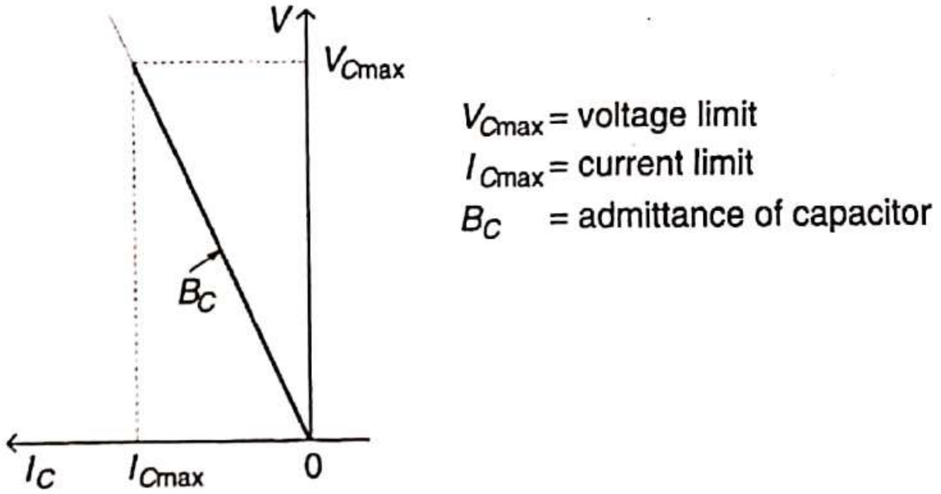


Figure [redacted] Operating *V-I* area of a single TSC.

The current in the TSC branch varies linearly with the applied voltage according to the admittance of the capacitor as shown by the V-I plot in above fig. The max. applicable voltage and the corresponding current are limited by the ratings of the TSC components (capacitor & thyristor switch).

iii) <u>Fixed Capacitor – Thyristor Controlled Reactor. (FC – TCR)</u> :—

A basic var generator arrangement using a fixed capacitor with a thyristor controlled reactor (FC-TCR) is shown in fig. (a) below

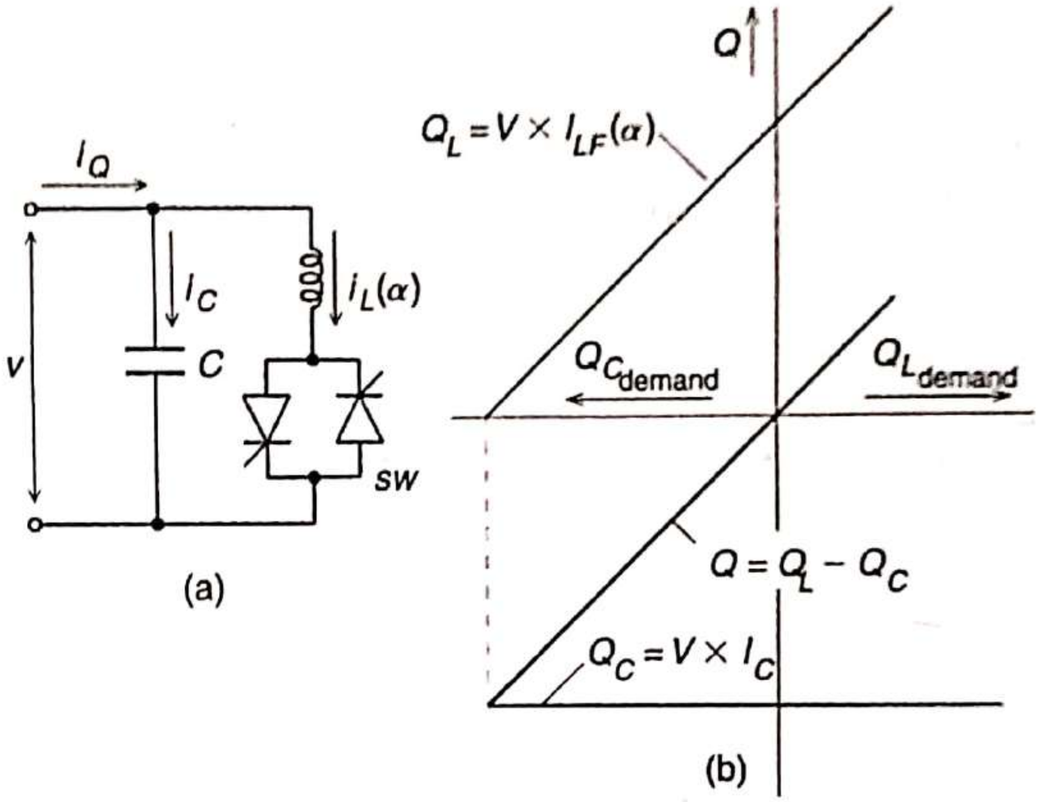


Figure [redacted] Basic FC-TCR type static var generator and its var demand versus var output characteristic.

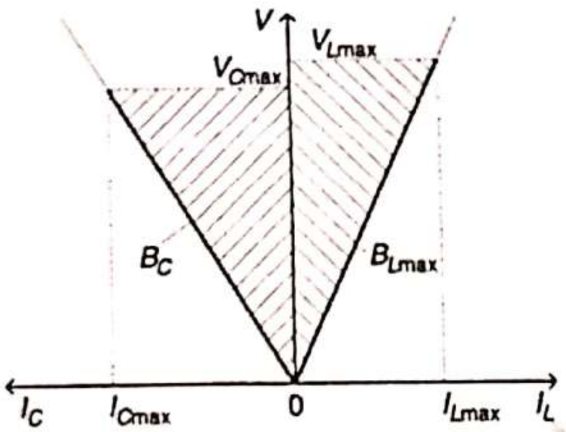
- The current in the reactor is varied by the method of firing delay angle control. The capacitor always injects the fixed amount of reactive power. An overall var demand versus var output characteristic as shown in Fig. (b).

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 max. capacitive var output, the thyristor controlled reactor is off ($\alpha = 90°$). To decrease the capacitive var output, the current in the reactor is increased by decreasing delay angle α. At zero var output, the capacitive & inductive currents become equal & thus the capacitive & inductive vars cancel out.

With a further decrease of angle α (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 TCR conducts current over the full 180° interval, resulting in max. inductive var output that is equal to the difference betn the vars generated by the capacitor & those absorbed by the fully conducting reactor



V_{Cmax} = voltage limit for capacitor
V_{Lmax} = voltage limit for TCR
I_{Cmax} = capacitive current limit
I_{Lmax} = inductive current limit
B_{Lmax} = max inductive admittance
B_C = admittance of capacitor

Figure Operating *V-I* area of the FC-TCR type var generator.

(c)

The V-I operating area of the FC-TCR is defined by the max. attainable capacitive & inductive admittances & by the voltage & current ratings of the major power components (capacitor, reactor & thyristor switch), as shown in above fig. (c). The ratings of the power components are derived from application requirements.

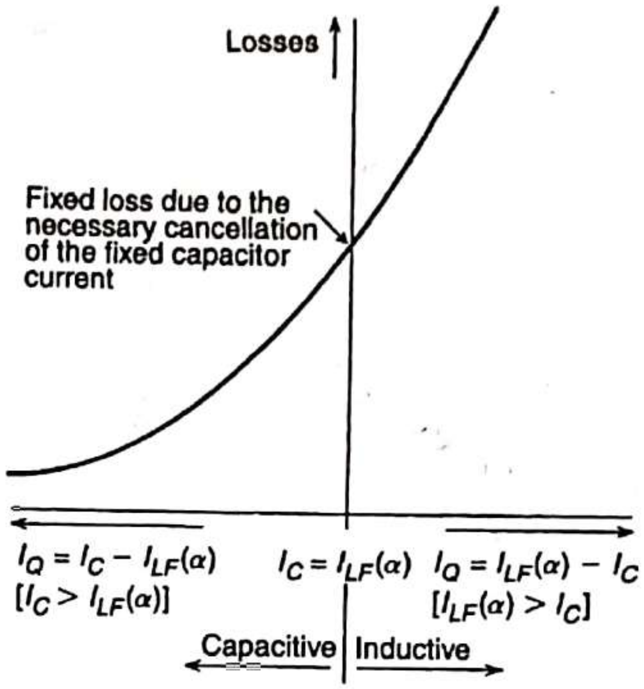


fig. (d) Loss Vs. var output chara. of FC-TCR.

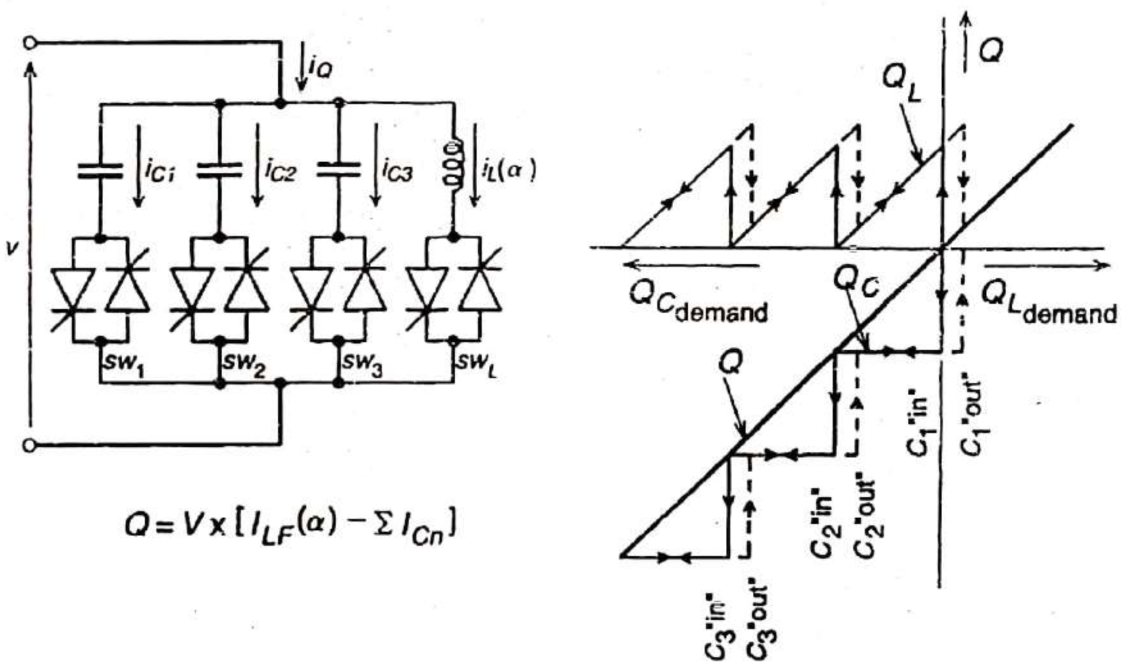
In addition to dynamic performance, the loss vs. var output characteristics of a var generator in practical applications is of major importance.

For the FC-TCR type var generator, there are three major constituents of the losses encountered:

i) the capacitor losses (these are relatively small)
ii) the reactor losses (these increase with the square of the current) &
iii) thyristor losses (these increase almost linearly with the current.).

Thus the total losses increase with increasing TCR current &, consequently, decrease with increasing capacitive var output.

iv) Thyristor Switched Capacitor – Thyristor Controlled Reactor (TSC-TCR):



(a) (b)

Fig. Basic TSC-TCR type static var generator (a) and its var demand versus var output characteristic (b)

The thyristor-switched capacitor, thyristor-controlled reactor (TSC-TCR) type compensator was developed primarily for minimizing standby losses and providing increased operating flexibility. A basic TSC-TCR arrangement is shown in fig.(a), 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. 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_{Cmax} /n range, where Q_{Cmax} is the total rating provided by all TSC branches. In this interval, one capacitor bank is switched in (by firing, for example, thyristor valve SW_1,) 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_{Cmax}/n to Q_{Cmax} /n, 2 Q_{Cmax} /n to 3 Q_{Cmax} /n, ..., and (n -1) Q_{Cmax} /n to Q_{Cmax} range by switching in the second, third, ..., and nth capacitor bank and using the TCR to absorb the surplus capacitive vars. The var demand versus var output characteristic of the TSC-TCR type var generator is shown in Fig. (b). As seen, the capacitive var output, Qc, is changed in a step-like manner by the TSCs to approximate the var demand with a net capacitive var surplus, and the relatively small inductive var output of the TCR, QL, is used to cancel the surplus capacitive vars.

In a way, this scheme could be considered as a special fixed capacitor, thyristor controlled reactor arrangement, in which the rating of the reactor is kept relatively small (1/n times the maximum capacitive output), and the rating of the capacitor is changed in discrete steps so as to keep the operation of the TCR within its normal control range.

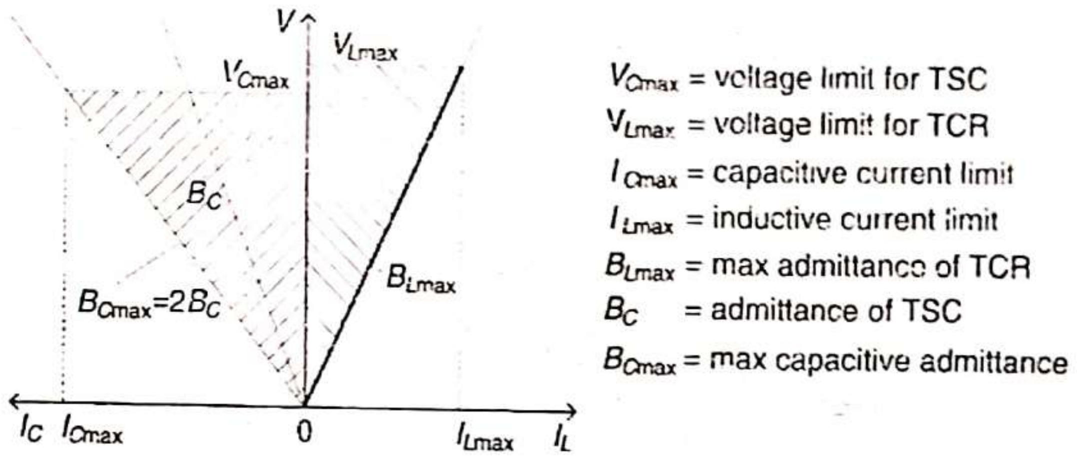


Fig. (c): Operating V-I area of the TSC-TCR with two thyristor-switched capacitor banks.

The *V-I* characteristic of the TSC-TCR type generator, shown for two TSCs in fig. (c), is also identical to that of its FC-TCR counterpart.

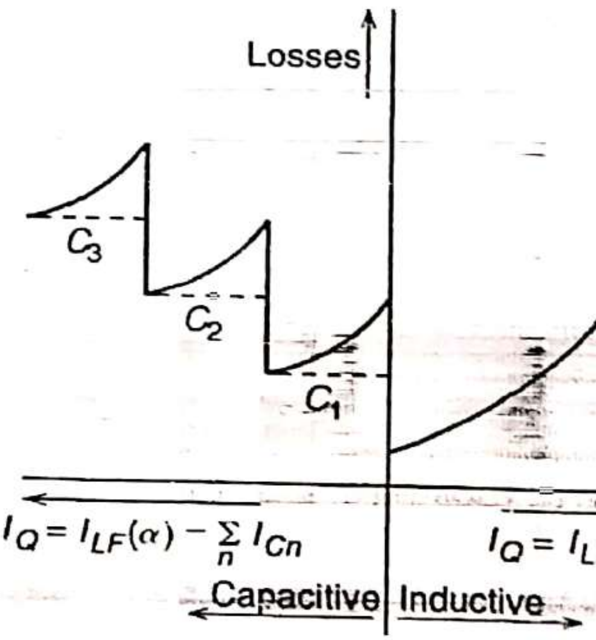


Fig. (d): Loss versus var output characteristic of the TSC-TCR

The loss versus var output characteristic of the TSC-TCR type var generator [fig. (d)] follows from its basic operating principle. At or slightly below zero var output, all capacitor banks are switched out, the TCR current is zero or negligibly small, and consequently, the losses are zero or almost zero.

As the capacitive output is increased, an increasing number of TSC banks are switched in with the TCR absorbing the surplus capacitive vars. Thus, with each switched-in TSC bank, the losses increase by a fixed amount. To this fixed loss, there are the added losses of the TCR, which vary from maximum to zero between successive switchings of the TSC banks.

2. Switching Converter Type VAR Generators

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.

Controllable reactive power can be generated by all types of dc to ac and ac to ac switching converters. The former group is generally called dc to ac converters or just converters, whereas the latter one is referred to as frequency changers or frequency converters or cycloconverters.

Converters presently employed in FACTS Controllers are the voltage-sourced type, but current-sourced type converters may also be used. Functionally, from the standpoint of reactive power generation, their operation is similar to that of an ideal synchronous machine whose reactive power output is varied by excitation control.

i) Static Synchronous Compensator (STATCOM):

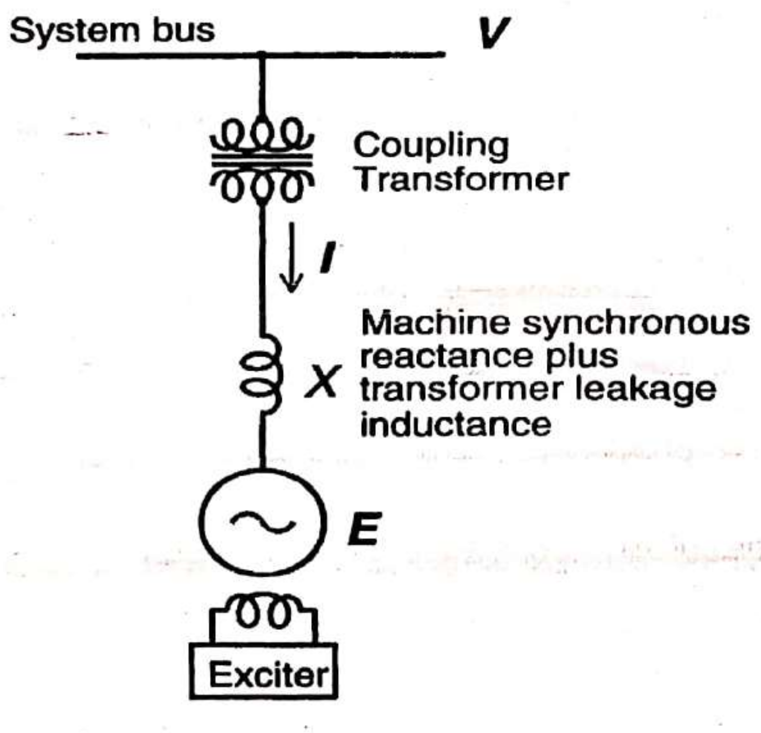


Fig. (a): Reactive power generation by a rotating synchronous compensator

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. STATCOM is one of the key FACTS Controllers. It can be based on a voltage sourced or current-sourced converter. From an overall cost point of view, the voltage-sourced converters seem to be preferred, and will be the basis for presentations of most converter-based FACTS Controllers.

The basic principle of reactive power generation by a voltage-sourced converter is akin to that of the conventional rotating synchronous machine shown schematically in Fig (a). For purely reactive power flow, the three-phase induced electromotive forces (EMFs), Ea, Eb, and Ec, of the synchronous rotating machine are in phase with the system voltages, Va, Vb, and Vc.

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:

$$I = (V - E)/X$$

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

$$Q = \frac{1 - \frac{E}{V}}{X} V^2$$

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. If the excitation of the machine is controlled so that the corresponding reactive output maintains.

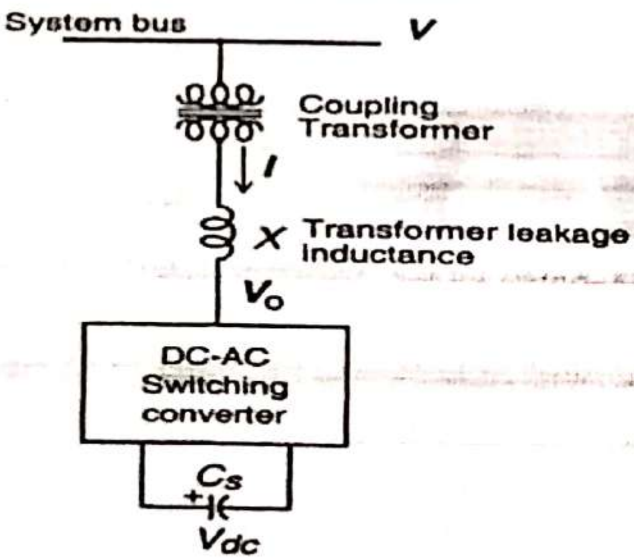


Fig. (b): Reactive power generation by voltage sourced switching converter.