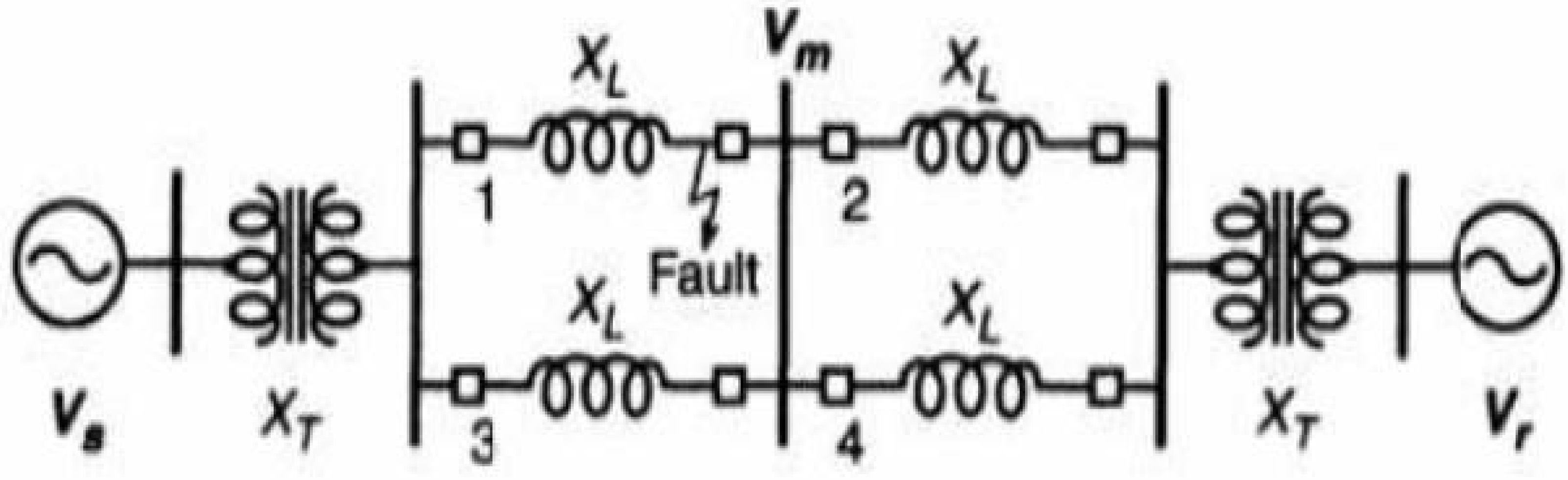
SVC–UNIT–2

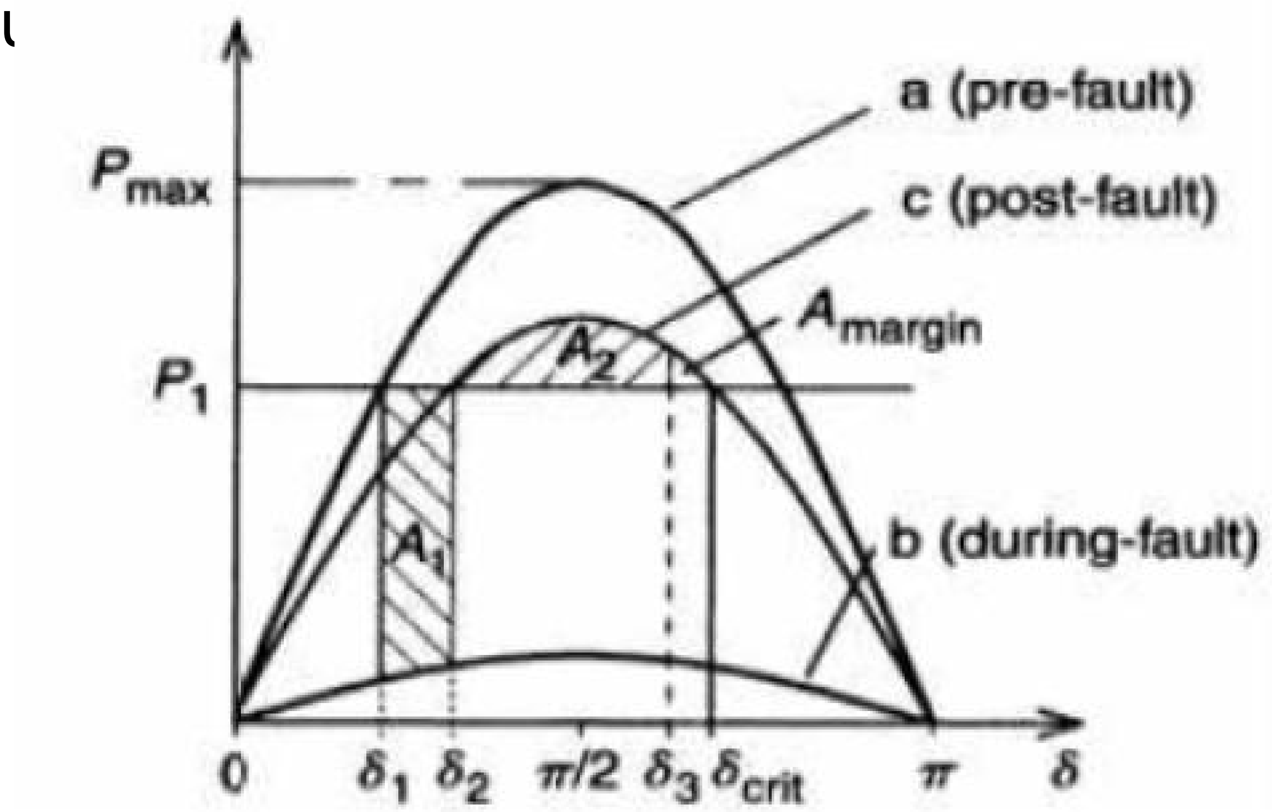
IMPROVEMENT OF TRANSIENT STABILITY

- **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**.

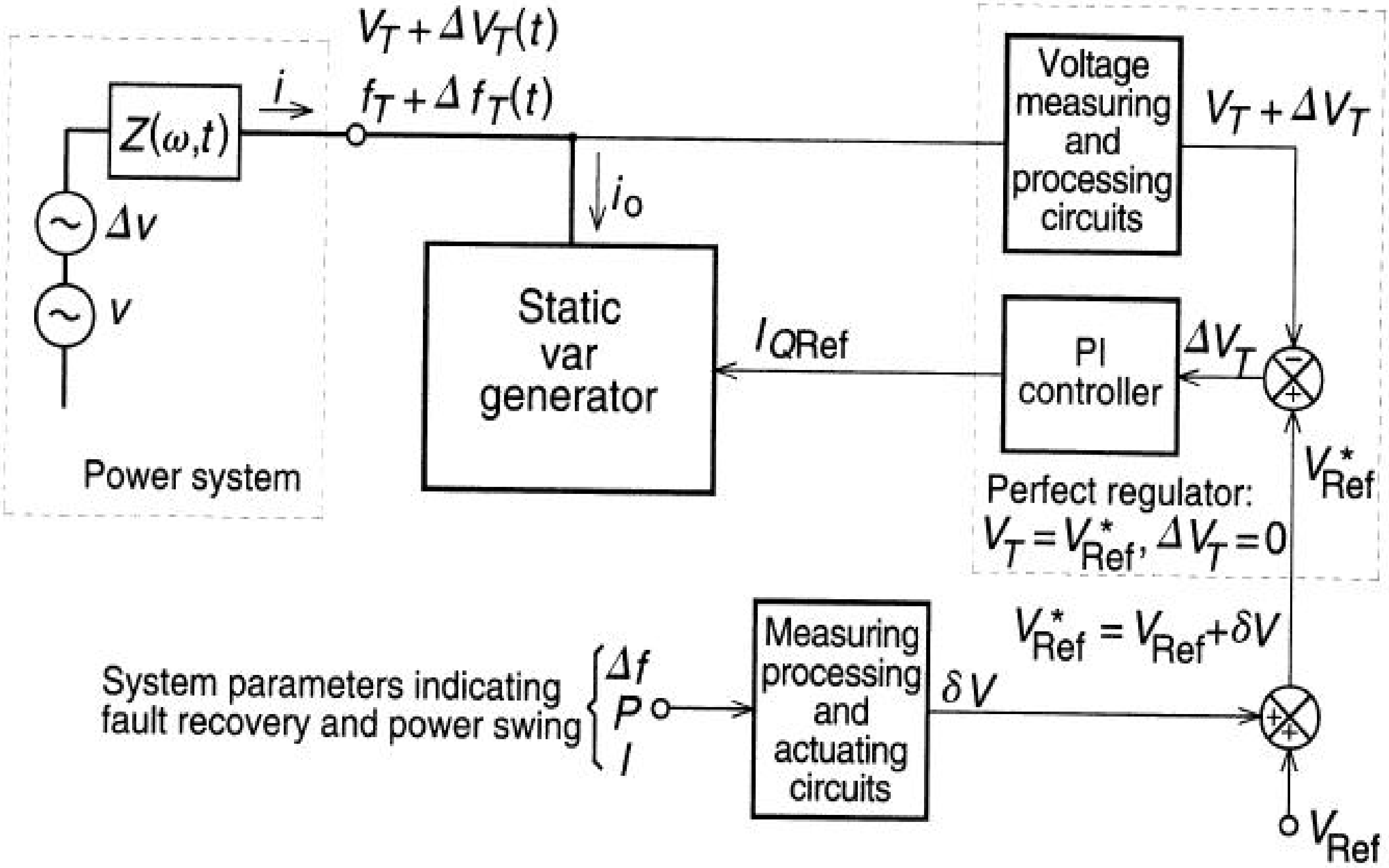

V_m
X_L
X_L
1
2
Fault
X_L
X_L
3
4
V_s
X_T
X_T
V_r

- Assume that the complete system is characterized by the P versus δ curve ‘a‘ and is operating at angle δ1 to transmit power P1 when a fau



- 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.

TRANSIENT STABILITY(Shunt Compensation)



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.**

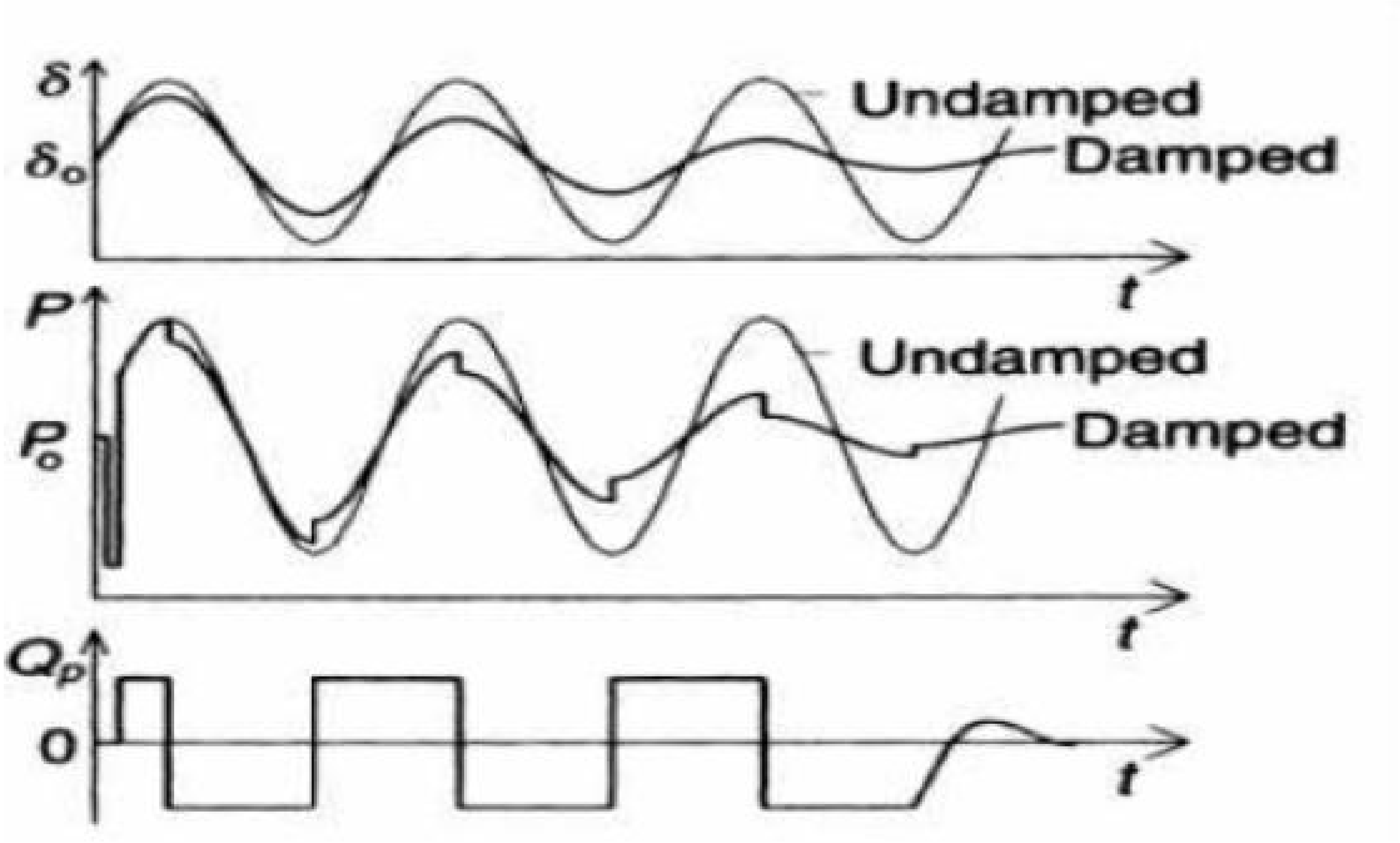
POWER OSCILLATION DAMPING

- The angle oscillation, 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 as it reduces the transmittable power.
- Mid point voltage should be varied through applied shunt compensation to damp out power oscillations in power system

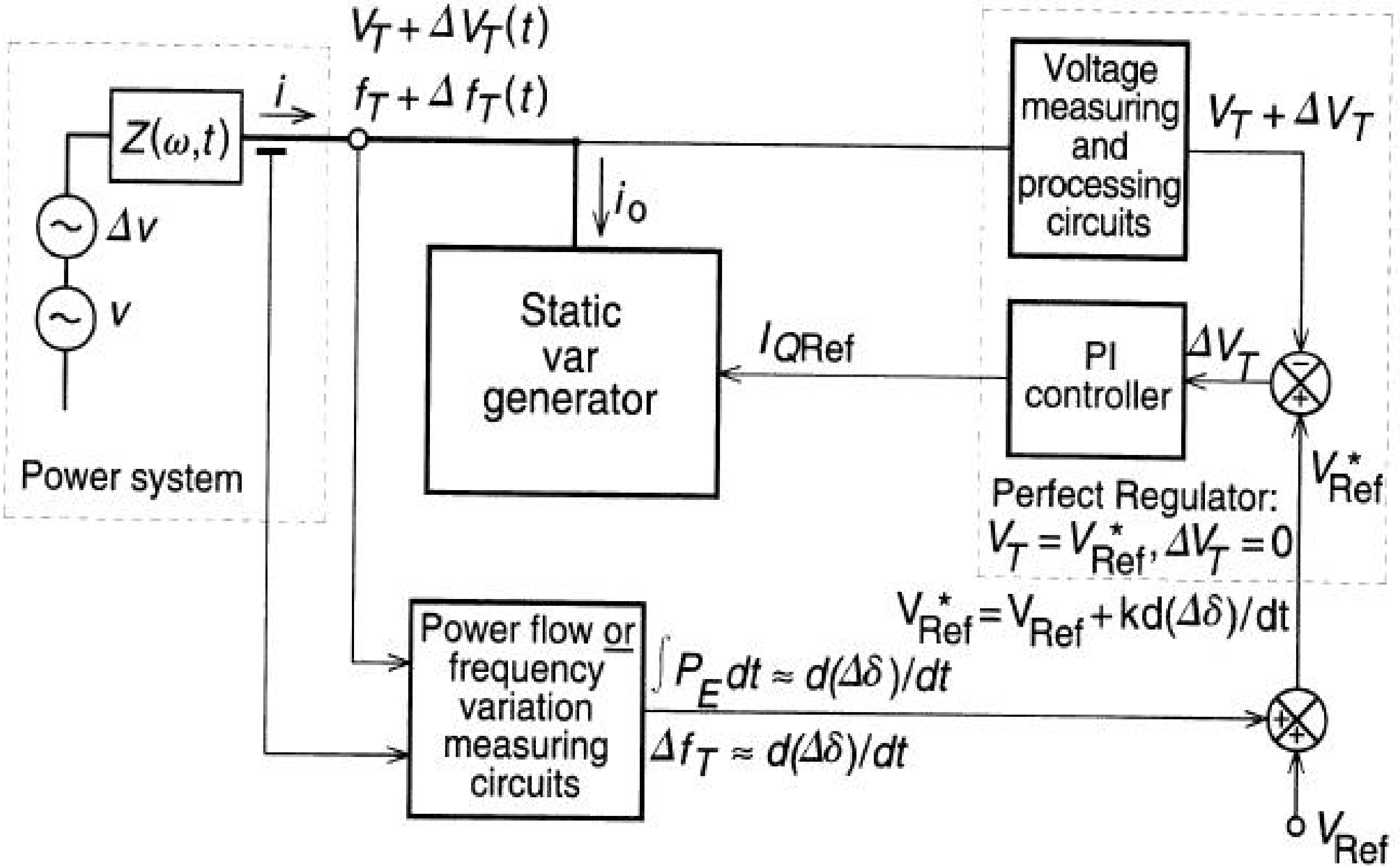
POWER OSCILLATION DAMPING

- When the rotationally oscillating generator accelerates and **angle δ increases *(dδ/dt/0)*,**
  - **the electric power transmitted must be increased to compensate for the excess mechanical input power.**
- Conversely, when the generator decelerates and **angle δ decreases (dδ/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

POWER OSCILLATION DAMPING



POWER OSCILLATION DAMPING (Shunt Compensation)



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(TSC–TCR)**

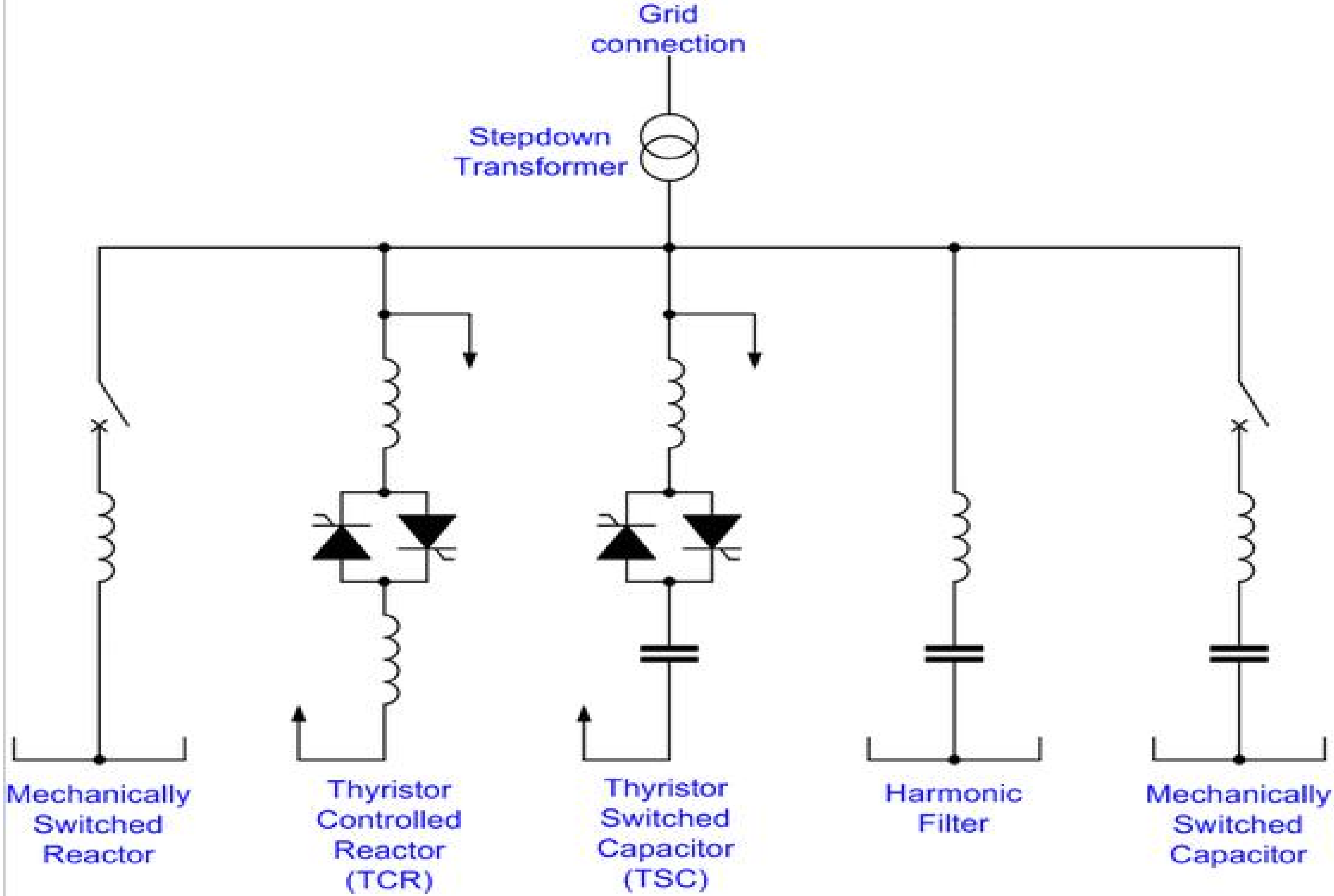
- **SWITCHING CONVERTER TYPE VAR GENERATORS:**
  - **STATIC CONDENSOR & STATIC COMPENSATOR (STATCOM)**

Static VAR Compensator

- A **static VAR compensator** is a set of electrical devices for providing fast-acting reactive power on high-voltage electricity transmission networks.
- SVCs are part of the Flexible AC transmission system device family, **regulating voltage, power factor, harmonics and stabilizing the system**.
- VCs are used in two main situations:
  - **Connected to the power system, to regulate the transmission voltage (‘Transmission SVC‘)**
  - **Connected near large industrial loads, to**

Static VAR Compensator

- In transmission applications, the SVC is used to regulate the grid voltage.
- If the power system's reactive load is capacitive (leading), the SVC will use thyristor controlled reactors to consume VARs from the system, lowering the system voltage.
- Under inductive (lagging) conditions, the capacitor banks are automatically switched in, thus providing a higher system voltage.


Grid connection
Stepdown Transformer
Mechanically Switched Reactor
Thyristor Controlled Reactor (TCR)
Thyristor Switched Capacitor (TSC)
Harmonic Filter
Mechanically Switched Capacitor

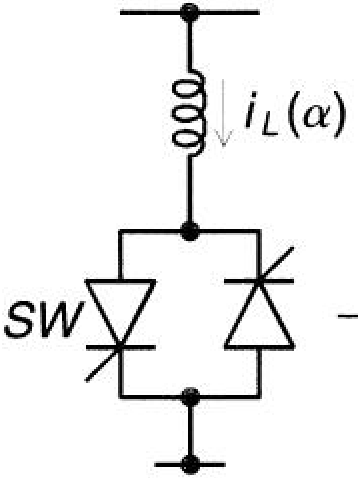
Advantage of Static VAR Compensator

- It increased the **power transmission capability** of the transmission lines.
- It **improved the transient stability** of the system.
- It **controlled the steady state** and temporary overvoltages.
- It **improved the load power factor**, and therefore, **reduced line losses** and **improved system capability.**

THYRISTOR–CONTROLLED REACTOR (TCR)

- A TCR is one of the most important building blocks of thyristor–based SVCs.
- **TCR used to absorb the excess reactive power in the system.**
- It can not be used alone, because the inductive nature of the power system load.
- It is normally used with thyristor switched capacitor (TSC), to provide the controlled reactive power generation.
- Single phase TCR is consist of a fixed (usually air core) reactor of inductor L, and a bidirectional thyristor valve (or switch)

- Currently available large thyristors can block voltage up to **4000 to 9000 volts** and conduct current up to **3000 to 6000 amperes.**
- 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 a ctor.

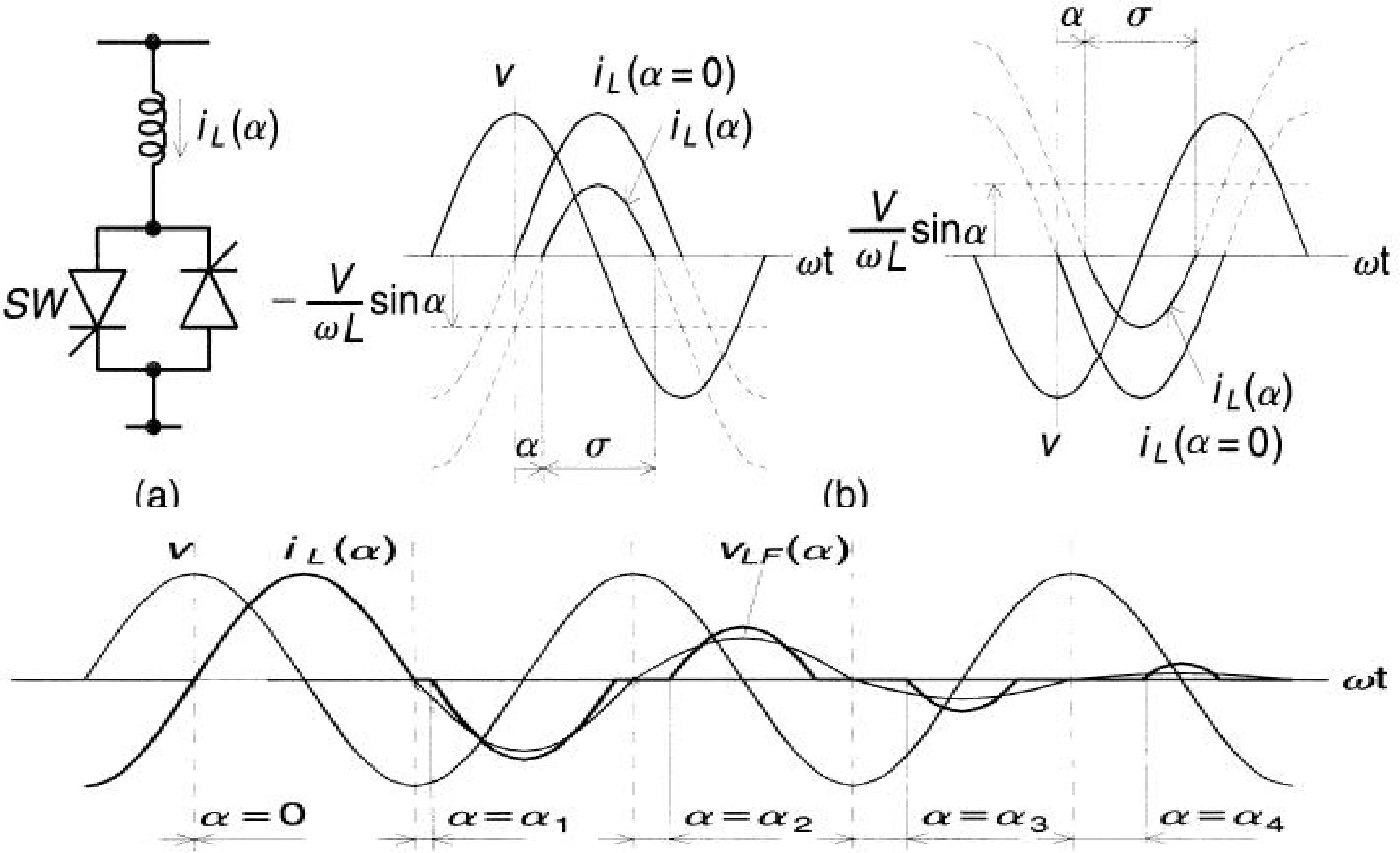


The Single-Phase TCR

- 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.

Current and voltages in TCR.



(a)

(b)

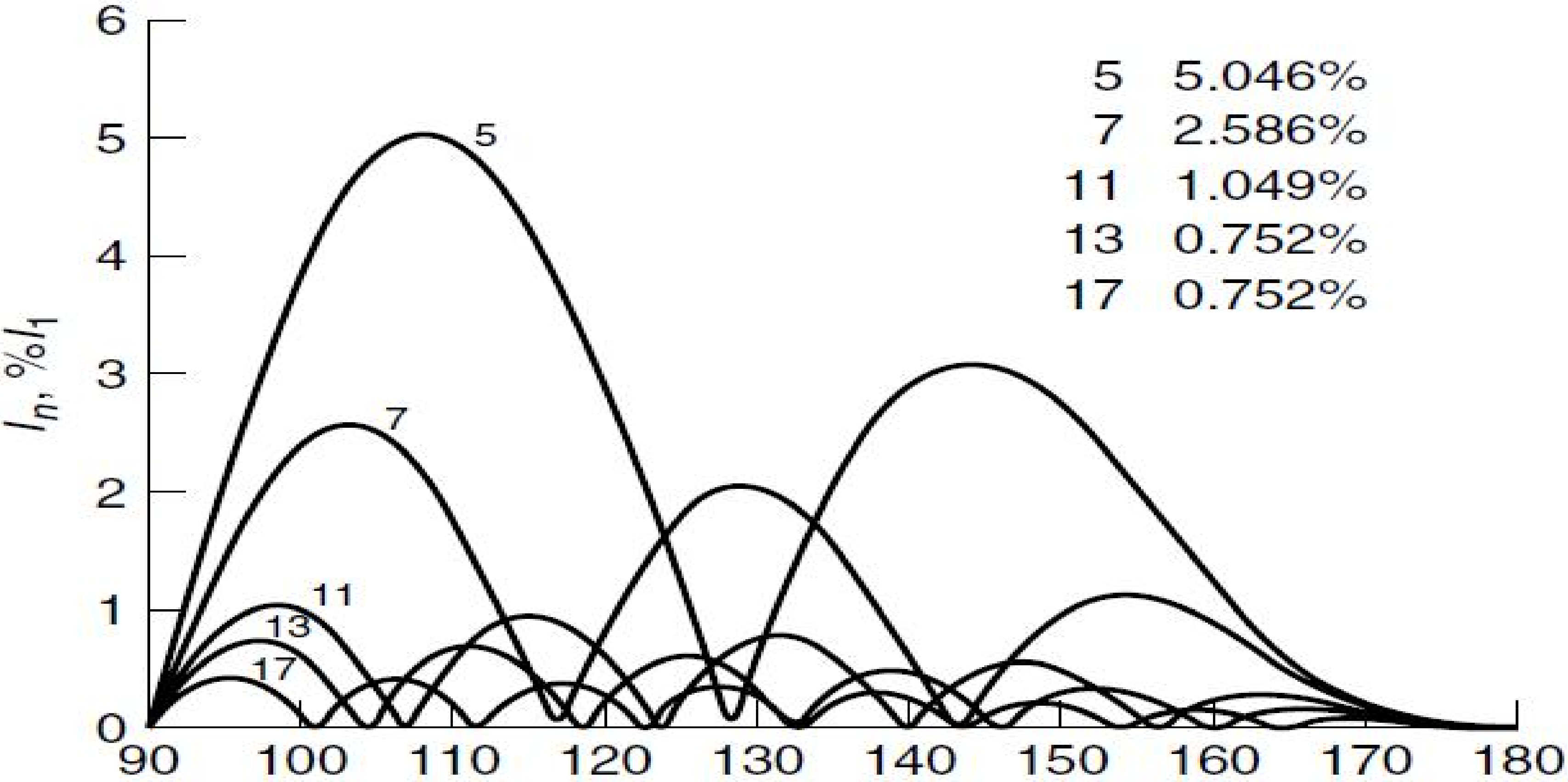
- When the gating of the valve is delayed by an angle α (0 ≤ α ≤ πl2) with respect to the crest of the voltage, the current in the reactor can be expressed with v(t) : V cos wt as follows:

$$i_L(t) = \frac{1}{L}\int_{\alpha}^{\omega t} v(t)\,dt = \frac{V}{\omega L}(\sin \omega t - \sin \alpha)$$

- Since the thyristor valve, by definition, opens as the current reaches zero, above equation is valid for the interval α ≤ wt ≤ π– α.

Harmonics in a TCR current

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 a in the* following equation:

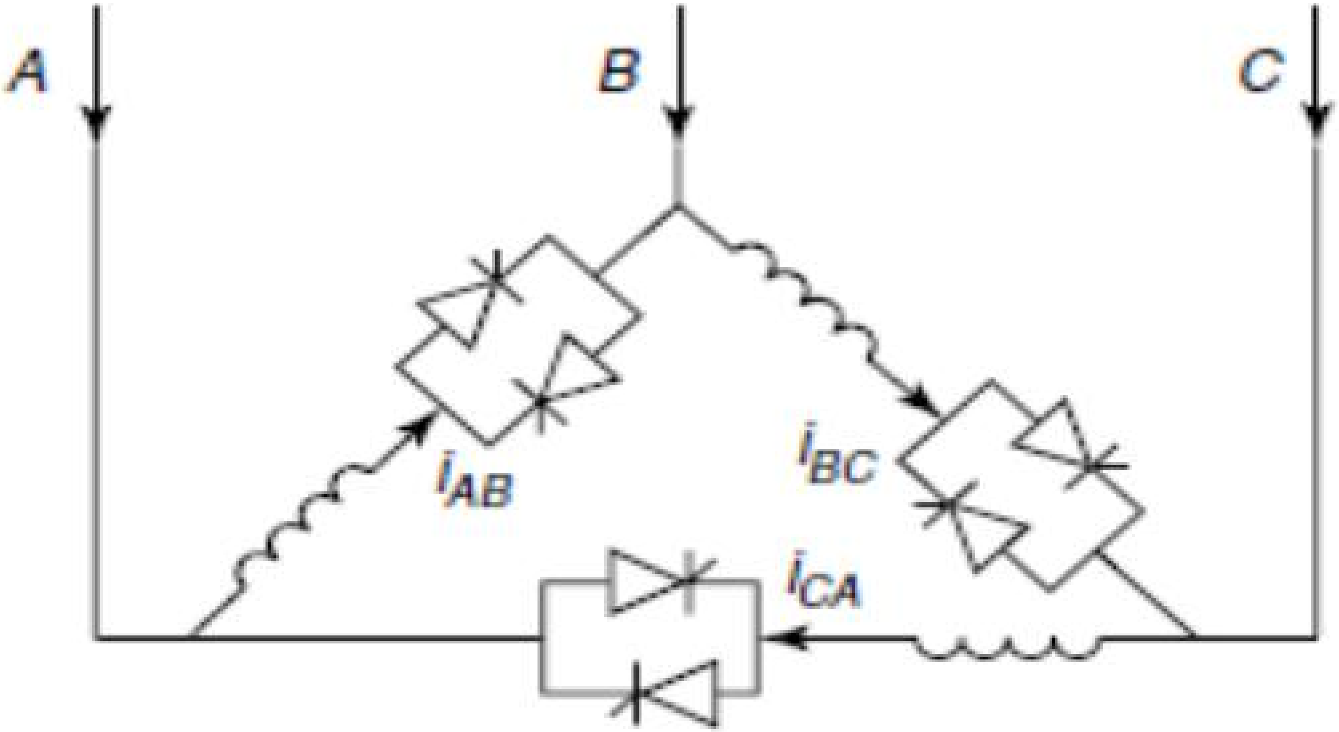
$$I_n(\alpha) = \frac{V}{\omega L}\,\frac{2}{\pi}\left[-2\,\frac{\cos\,\alpha}{n}\,\sin\,n\alpha + \frac{\sin(n-1)\alpha}{n-1} + \frac{\sin(n+1)\alpha}{n+1}\right]$$

$$= \frac{V}{\omega L}\,\frac{4}{\pi}\left[\frac{\sin\,\alpha\cos(n\alpha) - n\cos\,\alpha\sin(n\alpha)}{n(n^2-1)}\right]$$

where $n = 2k + 1$ and $k = 1, 2, 3, \ldots$

The 3-Phase TCR

- A 3-phase, 6-pulse TCR comprises three single-phase TCRs connected in delta



- The inductor in each phase is split into two halves, one on each side of the anti-parallel-connected thyristor pair, to prevent the full ac voltage appearing across the thyristor valves and damaging them if a short-circuit fault occurs across the reactor’s two end terminals.

- If the 3-phase supply voltages are balanced, if the three reactor units are identical, and also if all the thyristors are fired symmetrically—with equal firing angles in each phase
  - —then the symmetric current pulses result in both positive and negative half-cycles and the generating of only odd harmonics.
- The percentage values of harmonic currents with respect to fundamental—both in the phases and in the lines—are the same.

Advantages of TCR

- Flexibility of control and ease in uprating.
- Different control strategies can be easily implemented.
- The voltage reference and current slope can be controlled in a simple manner.
- Modular in nature, a TCR SVC can have its rating extended by the addition of more TCR banks, as long as the coupling transformer rating is not exceeded.

Limitations

- The TCRs do not possess high overload capability because the air-core design of their reactors.
- If the TCRs are expected to transiently withstand high overvoltages, a short-term overload capacity must be built into the TCR by design,
  - or additional thyristor-switched overload reactors may need to be installed.

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.

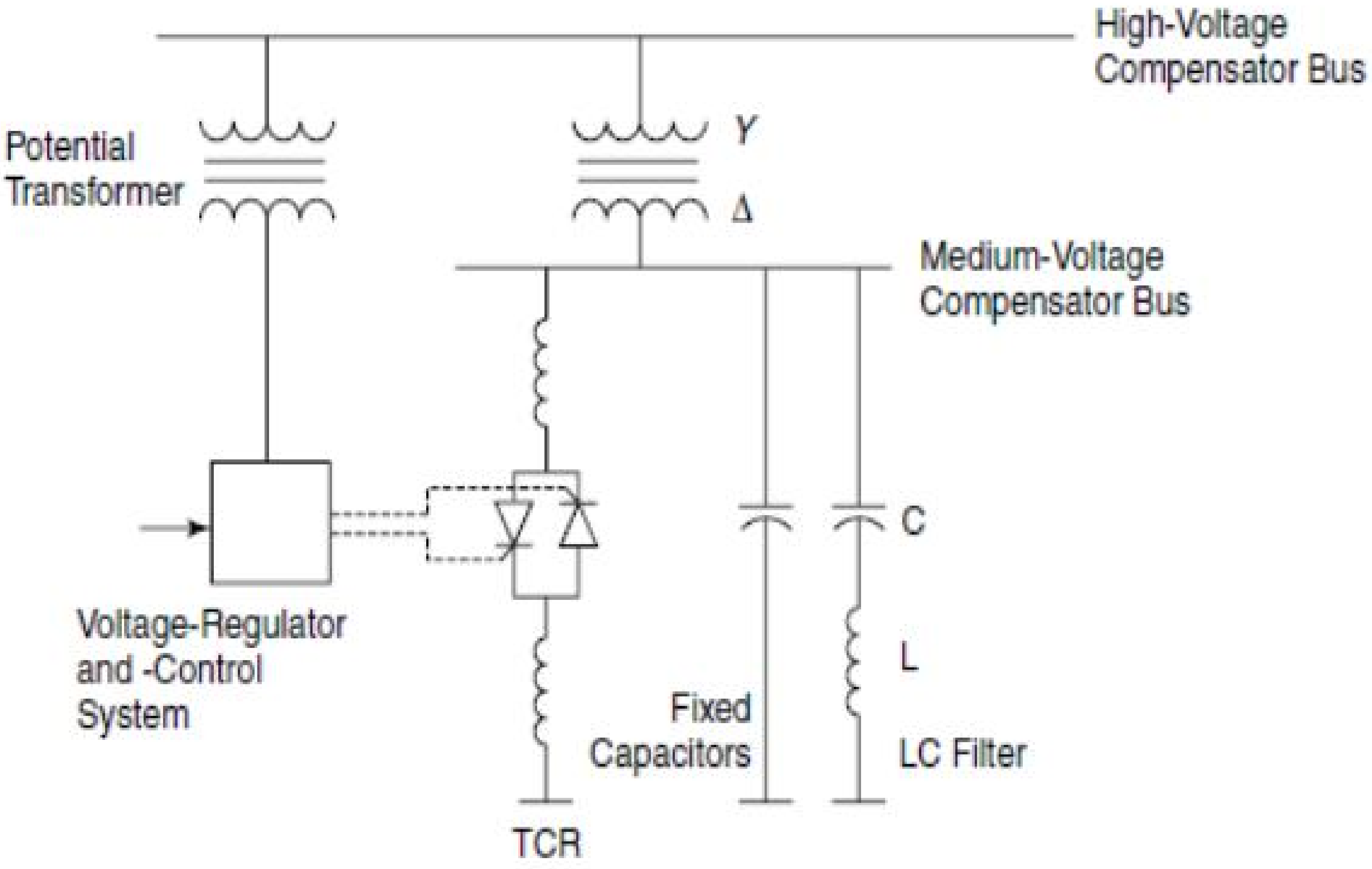
- **If the thyristor valves are fired exactly at the voltage peaks corresponding to α = 90° for the forward-thyristor valve T1 and α = 270° (90 + 180) for the reverse-thyristor valve T2.**

- 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.

FIXED CAPACITOR, THYRISTOR-CONTROLLED REACTOR (FC-TCR)

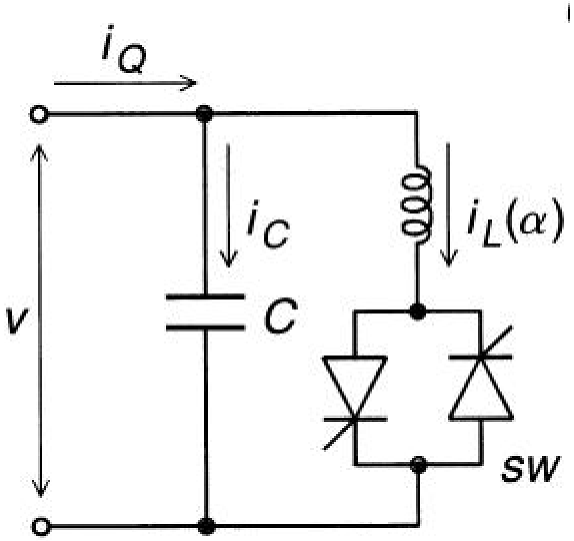
- The TCR provides continuously controllable reactive power only in the lagging power-factor range.
- **To extend the dynamic controllable range to the leading power-factor domain, a fixed-capacitor bank is connected in shunt with the TCR.**
- The fixed-capacitor banks, usually connected in a star configuration, are split into more than one 3-phase group.
- Each capacitor contains a small tuning inductor that is connected in series and tunes the branch to act as a filter for a specific harmonic order.

A 1-line diagram of a TCR compensator with fixed-shunt capacitors



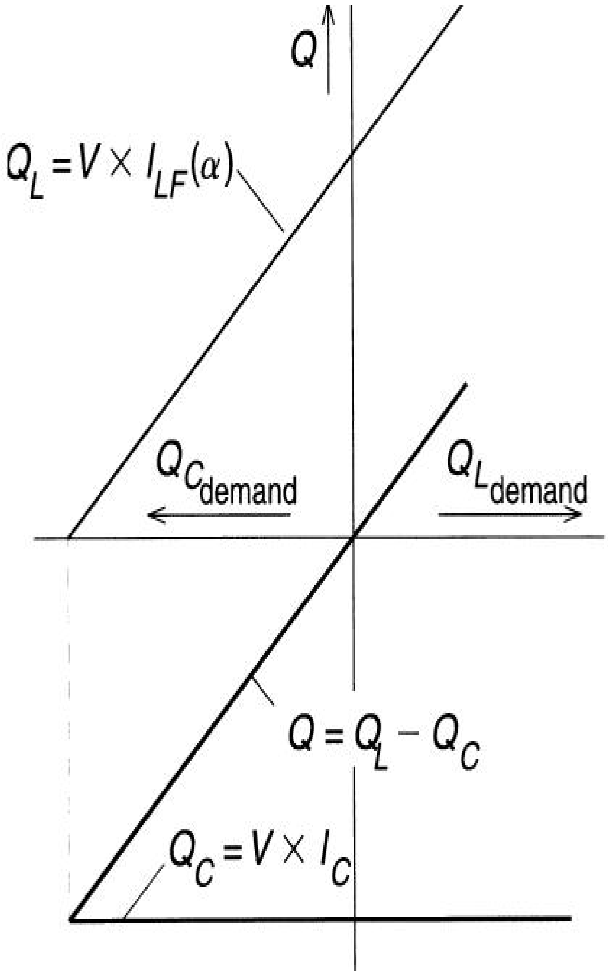
- The current in the reactor is varied by the method of firing delay angle control.
- The capacitor always injects generate the fixed amount of reactive power.
- So TCR will absorb the excess reactive power in controlled manner by varying firing angle.
- The trade of between the fixed capacitor and TCR will provide smooth control of SVC.

- During light load condition the transmission system, itself have the higher reactive power (leading PF)
- So to make unity p.f or better operation of SVC, the TCR rating should be higher than the fixed capacitor.
- Normally the capacitor are connected in star format.
- The fixed capacitor having a small inductance in series, hence it acting as passive LC filter.
- LC filter provide capacitive impedance at fundamental frequency and generate



- The LC filter provide lower impedance to selected harmonics (dominant harmonics produced by TCR) such as 5th, 7th ,11th....
- Each capacitor tuned for different frequency.
- Additional to third LC filter an LC high pass filter also connected with the system as shunt format.
- The fixed capacitor, thyristor controlled reactor type Var generator may be considered essentially to consist of variable reactor (controlled by delay angle α) and a fixed capacitor.

- The constant capacitive Var generation (Qc) of the fixed capacitor.
- Variable Var absorbtion (QL)of the thyristor controller reactor.
- Total output Q(SVC Var generation)
- At the maximum capacitive Var output, the thyritor controlled reactor is off(α=90) wrt peak.
- To decrease capacitive output, the current in the reactor is increased by decreasing delay



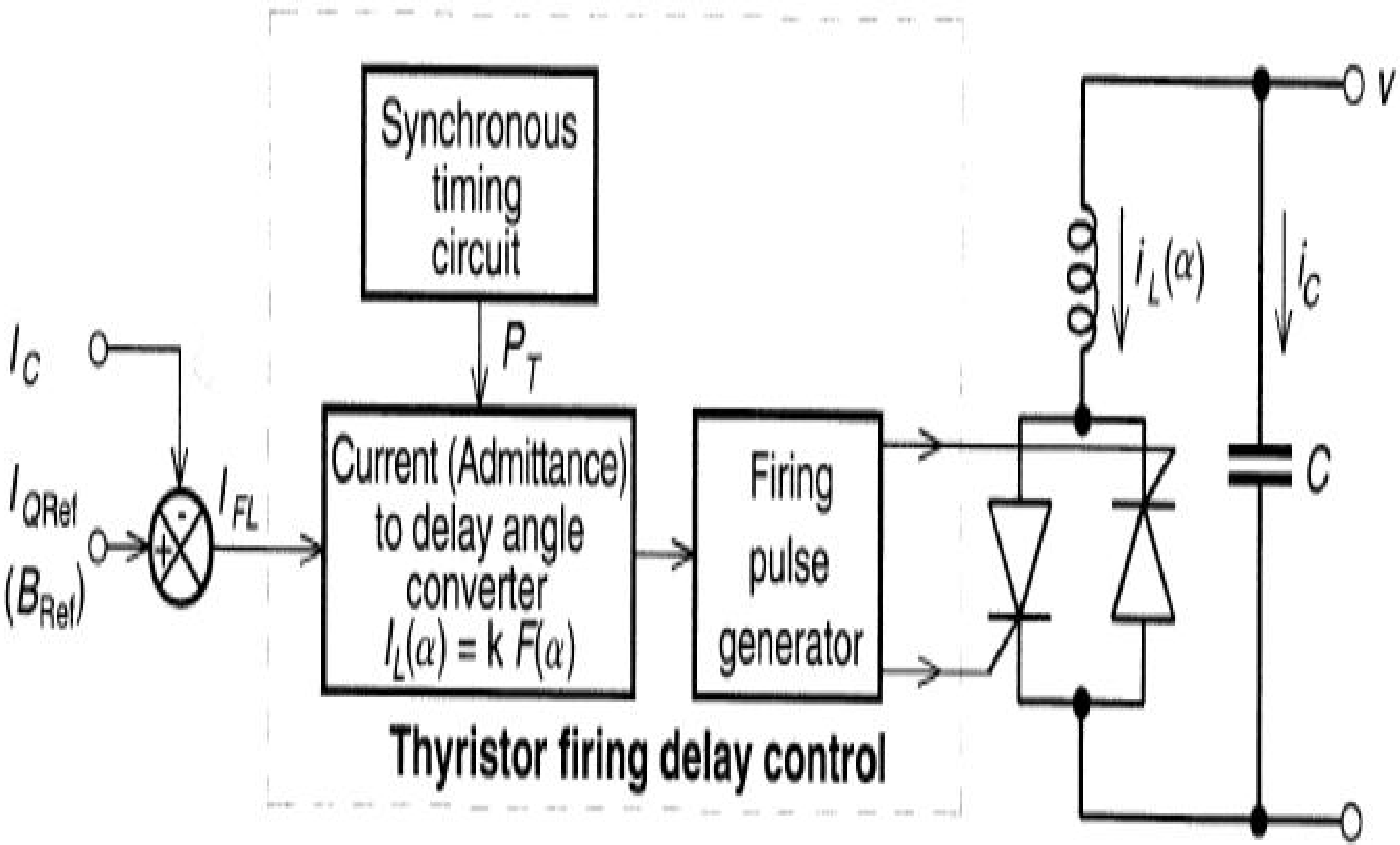
- **At zero Var output, the capacitive and inductive current are equal** (capacitive and inductive currents are cancelled out)
- To make net output is inductive Var(inductive current becomes larger than the capacitive current) by further decrease in angle α (assuming that the rating of the reactor is greater than that of the capacitor)
- At zero delay angle, the TCR conducts current over full 180 degree interval, resulting in maximum inductive var output.
- It is equal to the difference between the Var generated by the capacitor and those absorbed reactor.

Control of TCR in FC–TCR type Var generator

It has to provide 4 basic functions:

- Synchronous timing
- Reactive current (or admittance) to firing angle conversion
- Computation of the required fundamental reactor current I_{FL}
- Thyristor firing angle generation.

Control of TCR in FC–TCR type Var generator

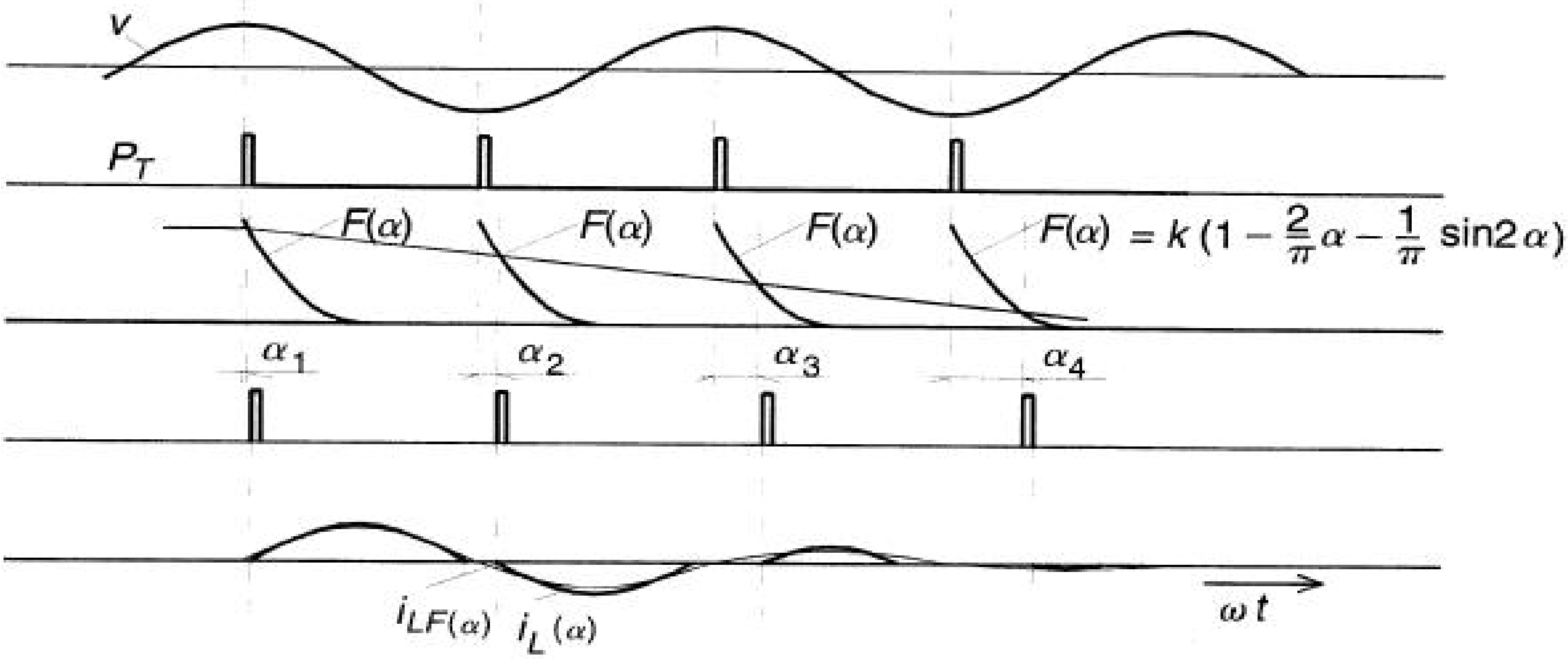


- Synchronous timing:
  - This function is normally established by a phase locked loop circuit that runs in synchronous with the ac system voltage.
  - It generates appropriate timing pulses with respect to the peak of that voltage.

- **Reactive current (or admittance) to firing angle conversion**
  - This can be provided by a real time circuit by using mathematical relationship between the amplitude of the fundamental TCR current $I_{LF}(\alpha)$ and delay angle α

admittance) to firing angle conversion (cont.)

- Several circuits are available literary for implementing.
- One of the method is analog function generator, it producing in each half cycle a scaled electrical signal



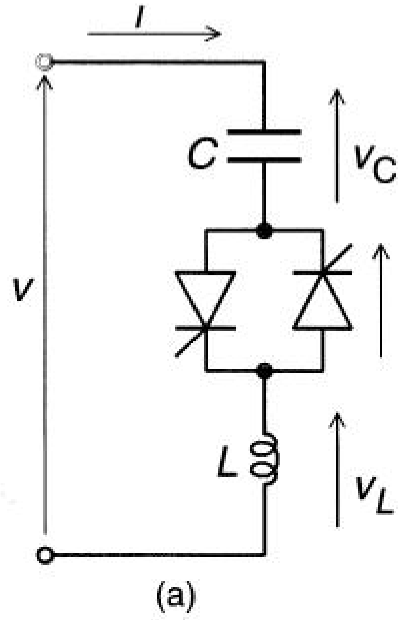
Another is digital “ look up table” for the normalized $I_{LF}(\alpha)$) versus α function which is read at regular interval starting $\alpha = 0$(peak of voltage) until the requested value is found, at which instant a firing pulse is initiated.

- Computation of the required fundamental reactor current
  - This is obtained by subtracting the (scaled) amplitude of the capacitor current, IC from I_{Cqref}(Positive polarity for I_{Cqref} means inductive output current, and negative polarity means capacitive output current.)

- Thyristor firing angle 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.

THYRISTOR–SWITCHED CAPACITOR (TSC)

- It consists of a capacitor, a bidirectional thyristor valve, and a relatively small surge current limiting reactor.



(a)

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 steadystate 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.

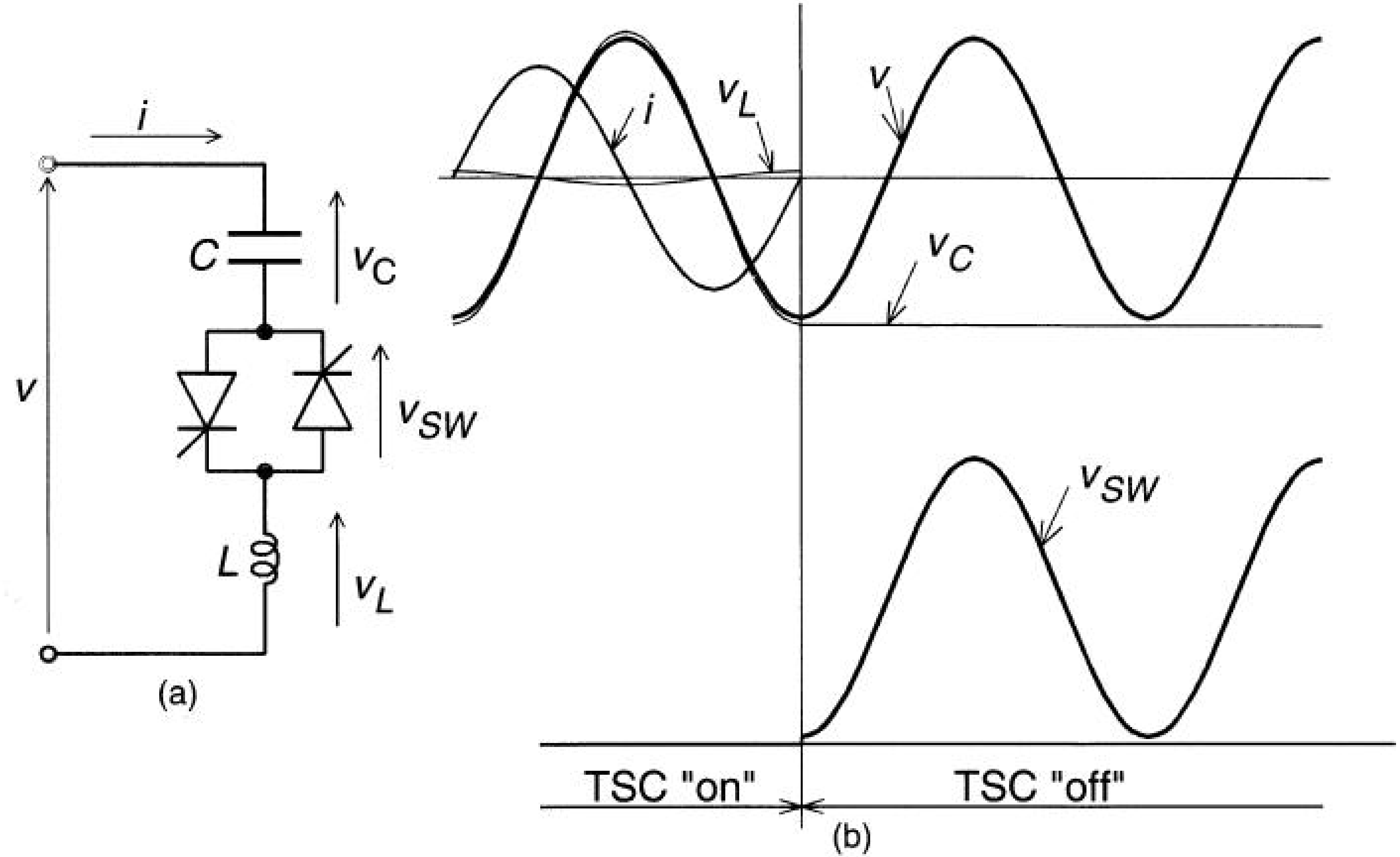
- This reactor is needed primarily
  - to limit the surge current in the thyristor valve under abnormal operating conditions (e.g., control malfunction causing capacitor switching at a ‘wrong time,‘ when transient free switching conditions are not satisfied);
  - it may also be used to avoid resonances with the ac system impedance at particular frequencies.

- Under steady-state conditions, when the thyristor valve is closed and the TSC branch is connected to a sinusoidal ac voltage source. V =V sin nwt.
- The current in the branch is given by

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

$$n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_C}{X_L}}$$

TSC



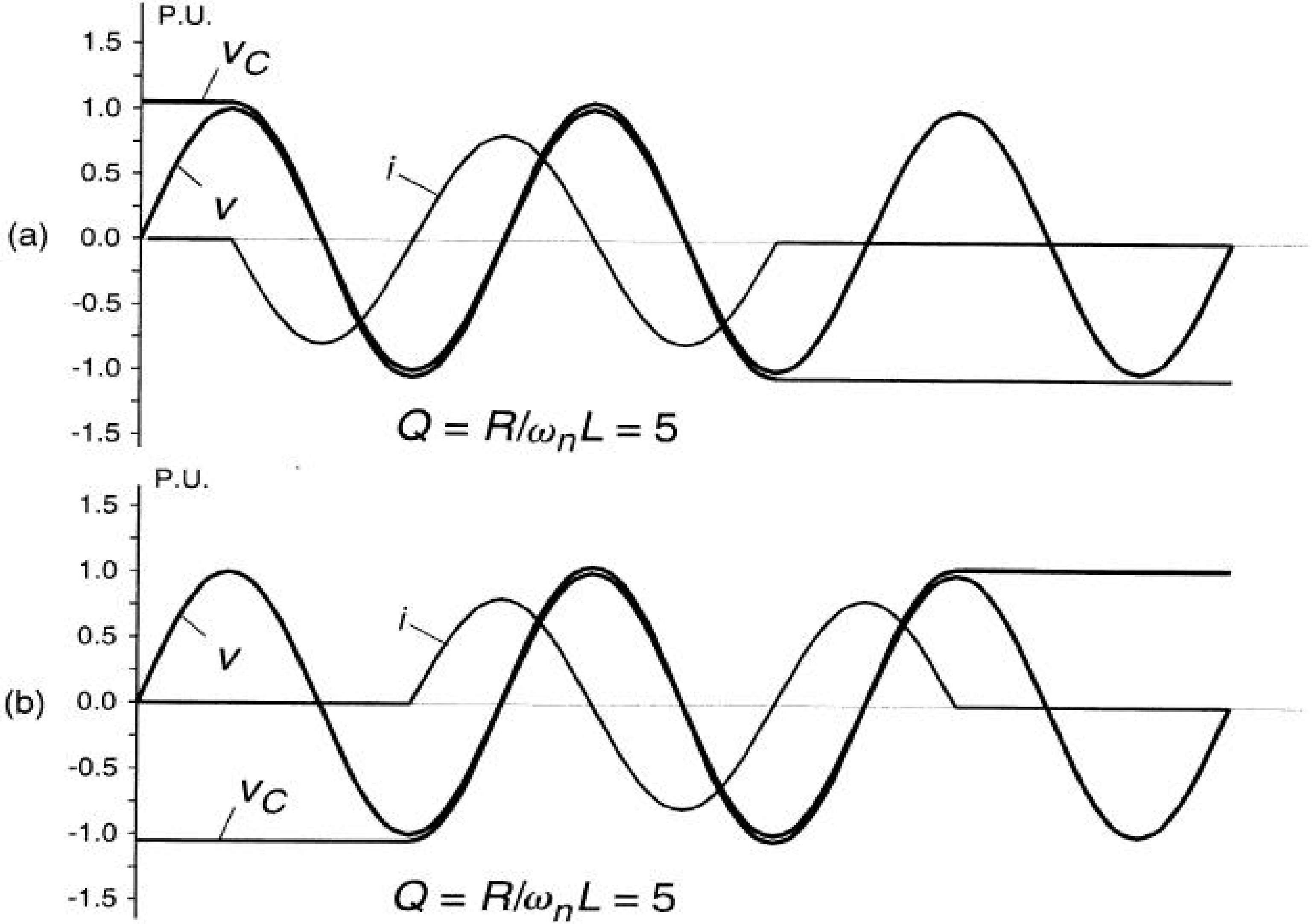
- Unlike the TCR, the TSC is only ever operated fully on or fully off.
- **An attempt to operate a TSC in ‘’phase control’’ would result in the generation of very large amplitude resonant currents,**
  - leading to overheating of the capacitor bank and thyristor valve, and harmonic distortion in the AC system to which the SVC is connected.

- **The TSC branch can be disconnected (“ switched out”) at any current zero by prial removal pulse for the thyristor valve.**
- At zero current crossing, the capacitor voltage is at its peak value.
- The disconnected capacitor stays charged to this value.
- Consequently, the voltage across the non conducting thyristor valve varies between zero and peak –to peak value of the ap
- The amplitude of th ss the capacitor is

$$V_C = \frac{n^2}{n^2 - 1} V$$

- If the voltage across the disconnected capacitor remained unchanged,
  - the TSC bank could be switched in again, without any transient, at the peak of the applied ac voltage, as illustrated for a positively and negatively charged capacitor in Figure(a) and (b), respectively

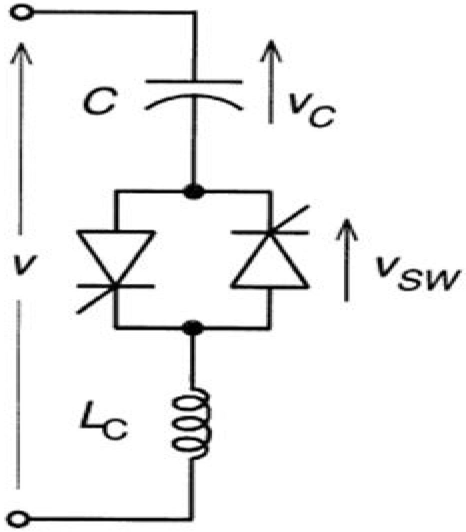
Waveforms illustrating transient-free switching by a thyristor switched capacitor.



Conditions for ‘transient-free‘ switching for the thyristor-switched capacitor with different residual voltages.

Two simple rules cover all possible cases:

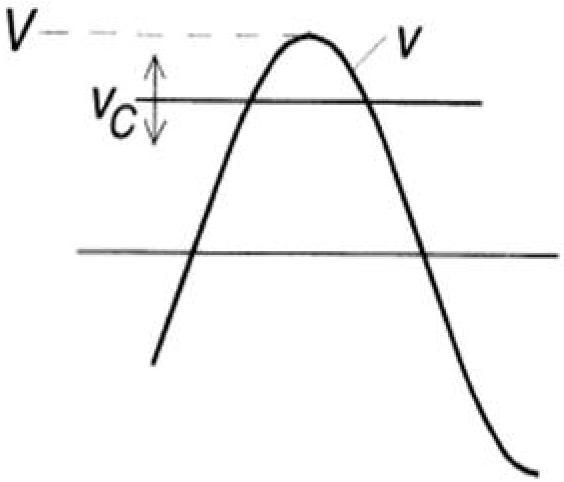
- (1) if the residual capacitor voltage is lower than the peak ac voltage (V, < V), then the correct instant of switching is when the instantaneous ac voltage becomes equal to the capacitor voltage; and



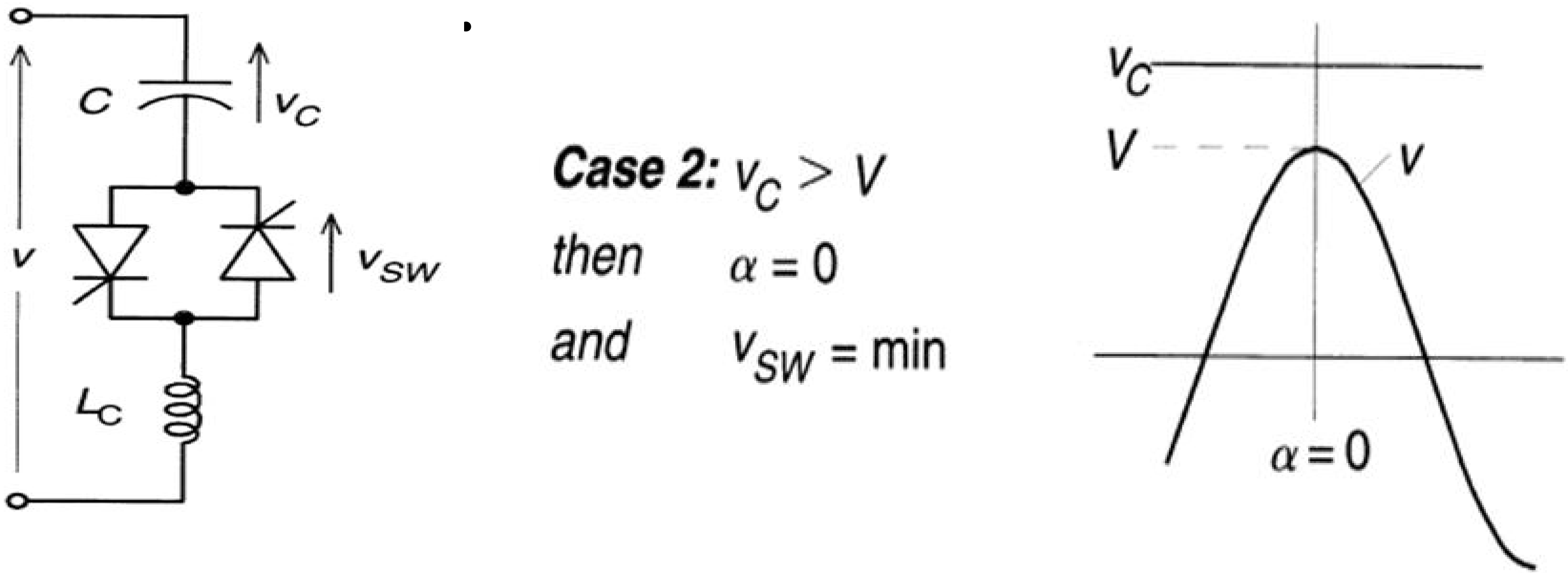
Case 1: $v_C \leq V$

then $v_C = v$

or $v_{SW} = 0$



- (2) if the residual capacitor voltage is equal to or higher than the peak ac voltage (V, ı V), then the correct switching is at the peak of the ac voltage at which the thyristor valve voltage is

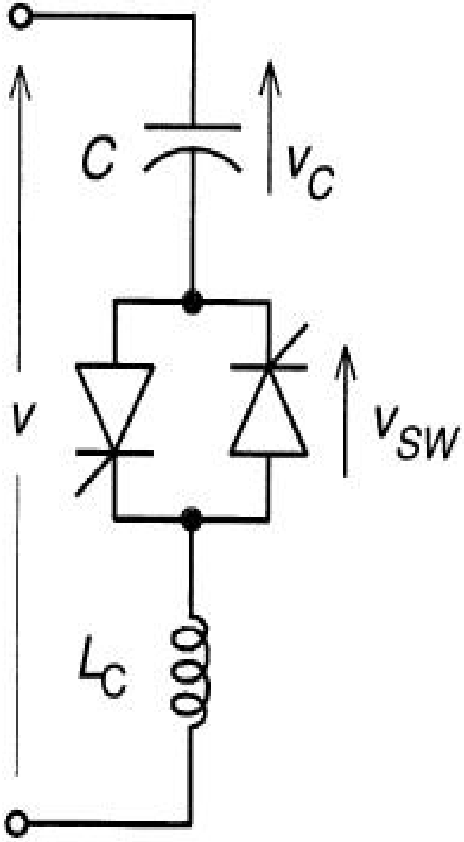


Case 2: $v_C > V$

then $\alpha = 0$

and $v_{SW} = \min$

Conditions for ‘transient-free‘ switching for the thyristor-switched capacitor with different residual voltages.



Case 1: $v_C \leq V$

then $v_C = v$

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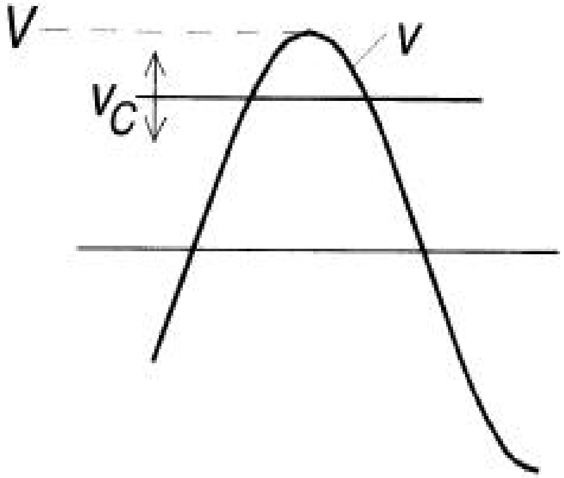
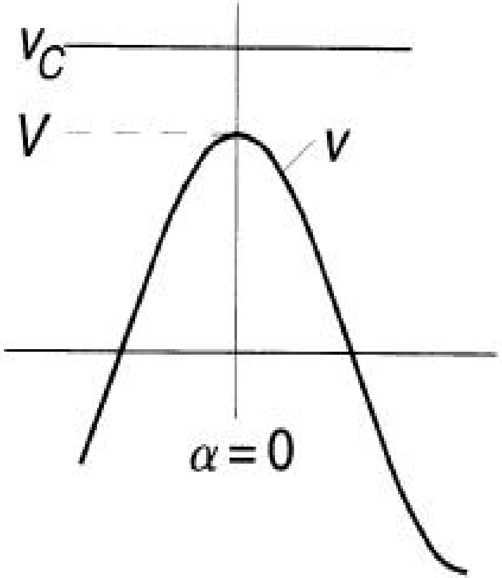


Case 2: $v_C > V$

then $\alpha = 0$

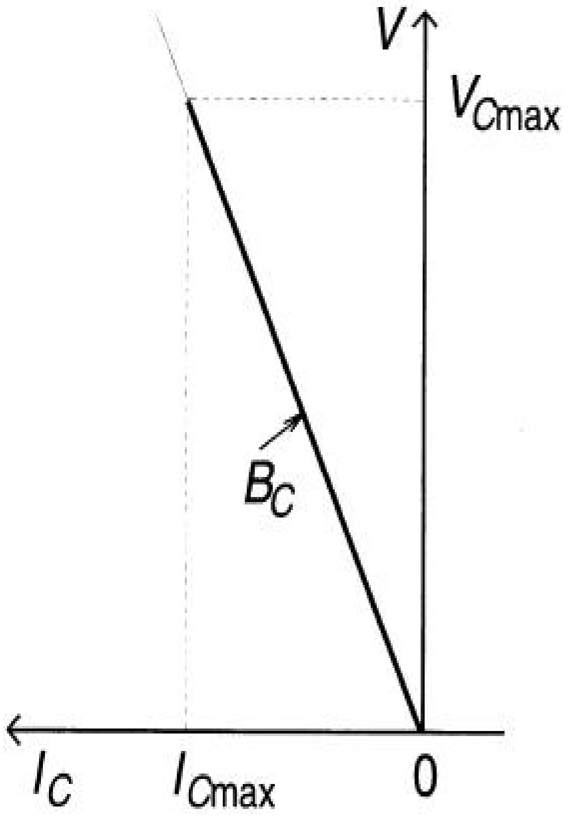
and $v_{SW} = \text{min}$



- The maximum possible delay in switching in a capacitor bank is one full cycle of the applied ac voltage,
  - is, **the interval from one positive (negative) peak to the next positive (negative) peak**.
- It also 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, that is, when the voltage across the thyristor valve is zero or minimum.**
- For this reason, a TSC branch can provide only

- In other words, the TSC branch represents a single capacitive admittance which is either connected to, or disconnected from the ac system.
- The **current in the TSC branch varies linearly with the applied voltage** according to the admittance of the capacitor as illustrated by the V–I plot.
- The maximum applicable voltage and the corresponding current are limited by the ratings of the TSC components (capacitor and thyristor valve).

Operating V–I area of a single TSC.



V_{Cmax} = voltage limit

I_{Cmax} = current limit

B_C = admittance of capacitor

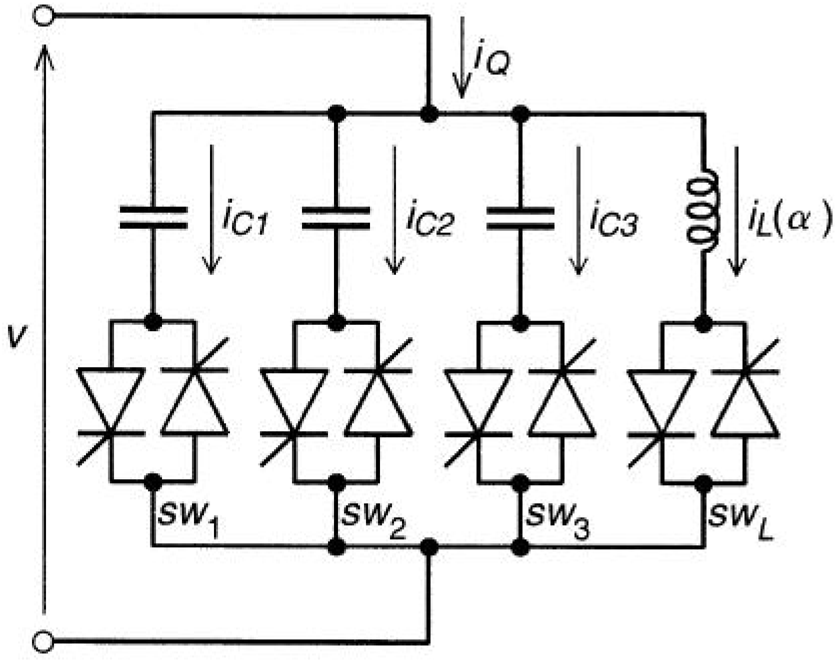
- To approximate continuous current variation,
  - several TSC branches in parallel (which would increase in a step-like manner the capacitive admittance) may be employed,
  - or, the TSC branches have to be complemented with a TCR.

Thyristor-Switched Capacitor, Thyristor-Controlled Reactor Type Var Generation

- TSC-TCR type compensator was developed primarily for **dynamic compensation** of power transmission systems with the intention of minimizing **standby losses and providing increased operating flexibility**.

Construction

- A basic single-phase TSC–TCR arrangement is shown in Figure.
- For a given capacitive output range, it typically consists of n TSC branches and one TCR.



Cont.

- The number of branches, n, is determined by
  - the operating voltage level,
  - maximum var output,
  - current rating of the thyristor valves,
  - and installation cost, etc.

- the inductive range also can be expanded to any maximum rating by employing additional TCR branches.

Working

- 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 Qcmax/n range,
  - **where Qcmax is the total rating provided by all TSC branches.**
- In this interval, one capacitor bank is switched in (by firing, for example, thyristor valve SW1,) 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**

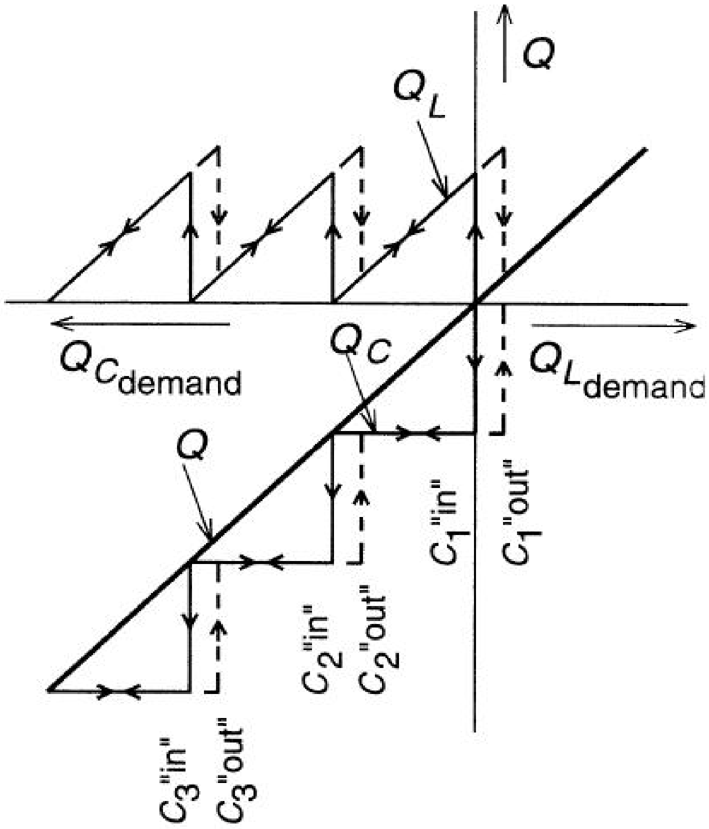
Cont.

- In the second, third, . . ., and nth intervals,
  - the output is controllable in the **Qcmax/n to 2Qcmax/n to 3Qcmax/n ,……. and (n-1)Qcmax/n to Qcmax** range by switching in the second, third, . .., and nth capacitor bank and using the TCR to absorb the surplus capacitive vars.

Cont.

- The var demand versus var output characteristic of the TSC–TCR type var generator is shown in Figure

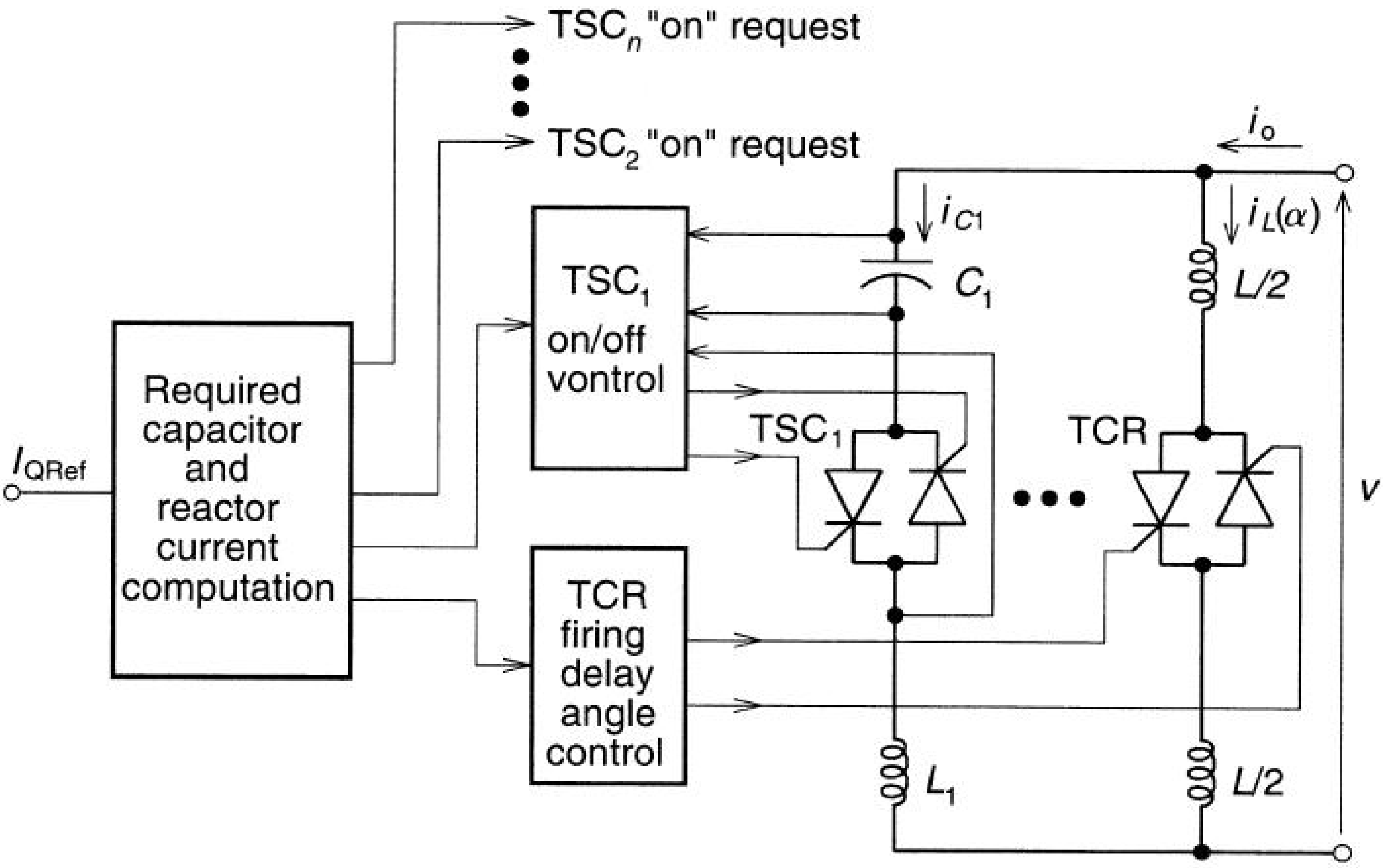
- As seen, the capacitive var output, Qr, is changed in a step-like manner by the TSCs to approximate the var demand with a net capacitive var surplus.
-
- and the relatively small inductive var output of the TCR, Q1, is used to cancel the surplus capacitive vars



Cont.

- In a way, this scheme could be considered as a special fixed capacitor, TCR arrangement, in which the rating of the reactor is kept relatively small
- 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.**

Functional control scheme for the TSC–TCR type static var generator

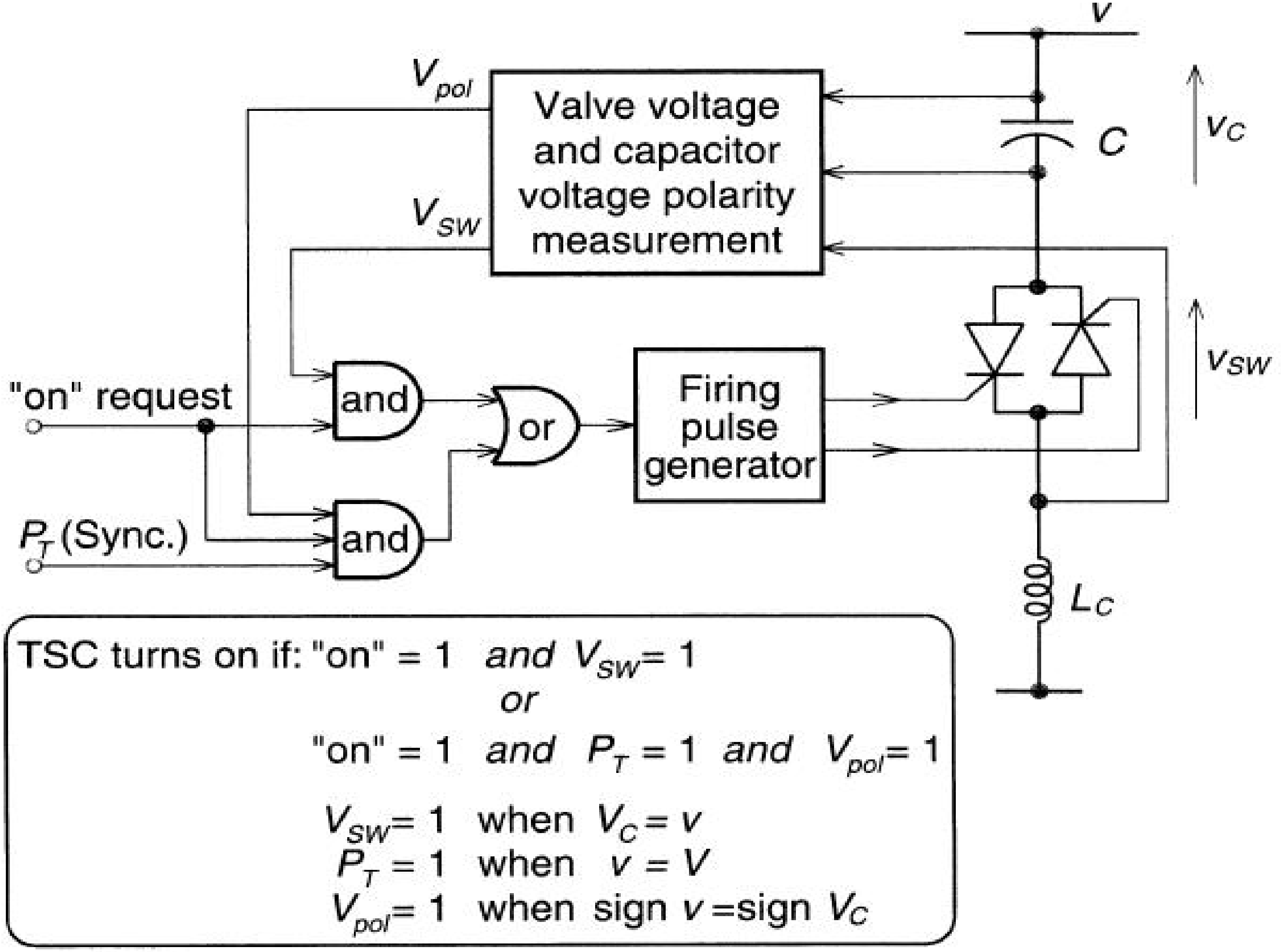


Cont.

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.

Functional logic for the implementation of ‘transient–free‘ switching strategy for the TSC.



TSC turns on if: "on" = 1 *and* $V_{SW} = 1$
or
"on" = 1 *and* $P_T = 1$ *and* $V_{pol} = 1$

$V_{SW} = 1$ when $V_C = v$
$P_T = 1$ when $v = V$
$V_{pol} = 1$ when sign v = sign V_C

Cont.

- The basic logic for the second function (switching of the TSC branches) is detailed in Figure.
- 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**

Cont.

- The response of the TSC-TCR type var generator, depending on the number of TSC branches used, may be somewhat slower than that of its FC-TCR counterpart.
- This is because the maximum delay of switching in a single TSC, with a charged capacitor, is one full cycle, whereas the maximum delay of the TCR is only half of a cycle.
- (Note that the maximum switching out delay for both the TSC and TCR is a half-cycle.)

Harmonics and Filtering

- The harmonics in a SVC are generated by the TCR. Neither TSC or TSR (Thyristor Switched Reactor) generate harmonics.

- The current harmonics generated by TCR can be classified into two categories:

1. Characteristic harmonics which are the harmonics present under ideal conditions such as sinusoidal, balanced AC voltages, equidistant firing pulses, and identical values of impedances in the three phases.

Characteristic Harmonics

- Under balanced operating conditions, the converter is supposed to produce fundamental and harmonics of the orders $5,7,11,13$,etc.
- Normal current harmonic produced on AC side are of the order $(np \pm 1)$
- Normal voltage harmonic produced on DC side are of the order (np)

where ‘n’ is any positive integer and ‘p’ is pulse number.

- The above mentioned normal harmonics are called as characteristic harmonics.

Non Characteristic Harmonics:

- The harmonics of the order other than characteristic harmonics are termed as non-characteristic harmonics.
- These are due to,
  - Imbalance in the operation of two bridges forming the 12 pulse converter
  - Firing angle errors
  - Unbalance and distortion in AC voltages.
  - Unequal transformer leakage impedances.

Harmonic Filters

- The presence of harmonics (both current and voltage) is viewed as `pollution’ affecting the operation of power systems.

- The injection of current harmonics by nonlinear loads also results in the distortion of the voltage waveforms due to the system impedances.

The adverse effects of the harmonics include

1. Harmonic over voltages, particularly during a transient which can also be sustained due to inrush current phenomena in transformers.
2. Increased losses in shunt capacitor banks and rotating machines whose impedances are much lower at harmonic frequencies than at system frequency

- The single-tuned shunt filters are commonly applied to eliminate harmonic currents injected by SVCs.
- The configuration of the single tuned filter is shown in Fig.

(a) Configuration

- The single-tuned shunt filters are commonly applied to eliminate harmonic currents injected by SVCs.
- The normalized impedance(Z/Xr) magnitude and its phase angle (φ) are given by

$$\frac{Z}{X_r} = \left[\left(\frac{R}{X_r}\right)^2 + \left(\frac{f}{f_r} - \frac{f_r}{f}\right)^2\right]^{1/2}$$

$$\phi = \tan^{-1}\left[\frac{X_r}{R}\left(\frac{f}{f_r} - \frac{f_r}{f}\right)\right]$$

$$f_r = \frac{1}{2\pi\sqrt{LC}}, \quad X_r = \sqrt{\frac{L}{C}}$$

Filter Design

- The filter design is based on the specification of various performance indices.
- Voltage distortion factor (Dn) at nth harmonic

$$D_n = \frac{V_n}{V_1},$$

- where Vn is the rms voltage at frequency f = nf0.
- Total harmonic ($$THD = \frac{1}{V_1}\sqrt{\sum_{n=2}^{N} V_n^2}$$ tion factor (THD)