Innovative Systems Design and Engineering
ISSN 2222-1727 (Paper) ISSN 2222-2871 (Online) DOI: 10.7176/ISDE
Vol.10, No.7, 2019

Literature Review of the Operational Characteristics of Static Var Compensator (SVC) in Electric Power System

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Abstract

This work looks into the literature review of the static Var compensator as it relates to the functional performance of the device in electric power system. Individual members of the compensator family are discussed with focus on the diverse operational features of the various constituting components. Modeling of the device is carried out, taking FC – TCR as a reference and deriving its susceptance with attention on the mathematical relationship of the constituent variables and their interdependency among one another. Graphical illustration between the adjustable susceptance and the thyristor firing angle is made, highlighting the imperturbability of the resonance angle on the linearity of the susceptance variation with respect to changing delay angle. Several mathematical computations are made to derive different equations that lead to some electric quantity expressions and their natural impart on the system. Steady and dynamic conditions of voltage and current characteristics are related, throwing light on the operational relationship among the three main parameters of the SVC device (B_{SVC} , Current and Voltage). The manner of reactive power exchange between the SVC equipments and the power system is explicitly explained, pointing at responsively fast control mechanism via the thyristor angle for adequate reactive power exchange and the consequent system compensation. The conductivity of TCR, under its independent existence as an SVC compensator or as a branch of other SVC devices is considered to reveal the effect of conduction angle and the thyristor firing angle in determination of flow of reactor current on the branch. Effect of SVC harmonics on power system is considered , and a brief suggestion made on the effective means of harmonics control in power system

Keywords: operational characteristics , power system, static Var compensator
DOI: 10.7176/ISDE/10-7-02
Publication date: August 31st 2019

SECTION I
INTRODUCTION

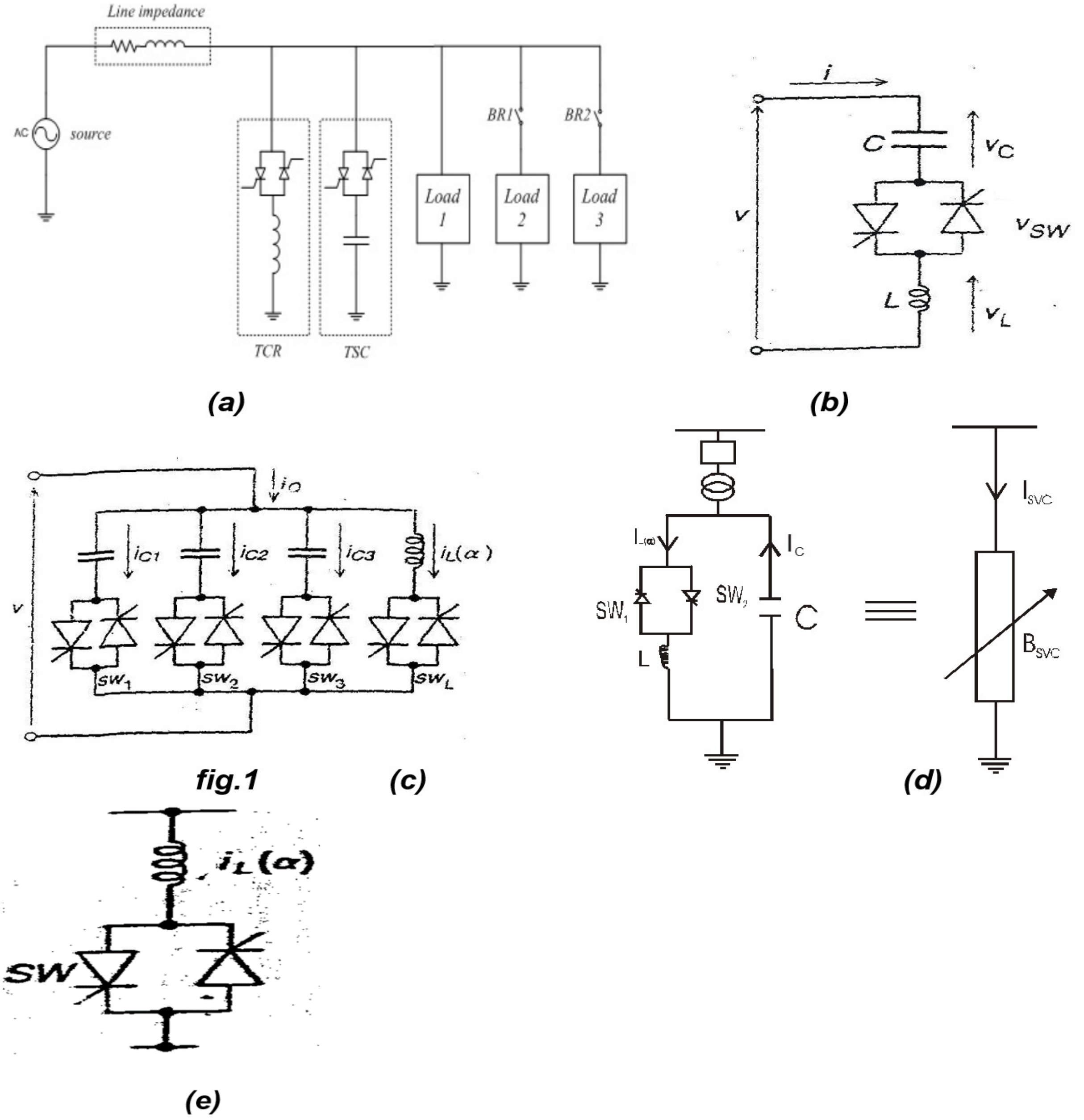
Facts concept application in electric power system has enjoyed enormous appreciation in the system's operation since advent of the technology. Solutions to some age long problems such as system transient instability, poor sub-synchronous resonance control (SSRC), regular occurrence of system fault, inadequate power flow as well as system power oscillation ,has creditably offered more courage to transmission and distribution system operators and accorded a loud applaud for more research into the improvement of FACTS controllers for optimization of system power transfer potential.

Following the usual reduction in bus villages of a heavily loaded system, several number of line equipments suffer great deal during the system power transfer. In most cases, more currents usually flow on the line to compensate for voltage deficit in order to convey the required amount of power to the receiving end. Most often, a high degree of current-flow extremely detrimental to the system equipments are being drawn along the lines, thus, resulting some damages and sudden network breakdown. In effect, the badly affected devices are being removed and replaced ; thereby, resulting a heavy cost of system maintenance and operation.

However, such power system problems can procure a lasting solution through a systematic placement of FACTS equipments at the suitable locations of the power network. In the case of abnormal voltage drops at the system buses, Static Var compensator (SVC), a family member of shunt controllers can augment the voltage of the buses where they are connected through variation of susceptance at those strategic buses (eg. FC-TCR),thus, upgrading the voltages at different buses of the entire power network to equal or approximately equal to the system nominal voltage so as to maintain the normal power flow along the line.

The regulation of bus voltages within the system by the SVC, in this case, is actualized by reactive power injection and absorption. With static Var devices on the specified system buses, the voltage drop at various buses is accompanied with automatic activation of the device through a suitably designed control system to inject current (capacitive) from a fixed set of capacitor bank. This allows the inflow of reactive power into the system to maintain a normal voltage level on the system buses. Conversely, when the system bus voltages rise beyond normal, more especially during the period of light load on the system, the static var equipments can be sensitized to absorb reactive power from the line, through the out flow of inductive current from the power line down the inductor branch(TCR) of the compensators to enable a proportional decrease of the bus voltages as determined by the automatic control unit. This is mostly obtained in the case of FC-TCR, TSC-TCR equipments where the operational compensation of the devices is effectively manned by special control system through the gate-pulse application of thyristor valves. Other sub-set members of the SVC family include TCR , TSC, TSR etc. Fig.1.0 below shows the schematic diagrams of different types of static Var compensators.

There are nine sections that make up this work, starting with introduction which gives the general idea of the subject matter in section I. Section II leads to the first static Var compensator ,FC-TCR , and its modeling as discussed in this article. In section III , light is extensively thrown on the reactive power exchange between SVC and the hosting power network .Effective trend of reactive power monitoring and the attendant sensitization of the device by a control system for compensation action dwells section IV; followed by the impart of TCR segment on rector current- flow with respect to conduction and thyristor angle control as considered in section V. Section VI looks into the effect of some selected thyristor firing angles on the equivalent reactance of a thyristor controlled reactor, TCR ; this is antecedent to harmonics generation and control in section VII as relates to TCR segment of SVC equipments. Discussion on thyristor switched capacitor occupies section VIII ; while, integration of some number of TSCs in combination of a single TCR circuit for adequate reactive power regulation, and in formation of a TSC – TCR composite characterizes section IX.



(a) (b)

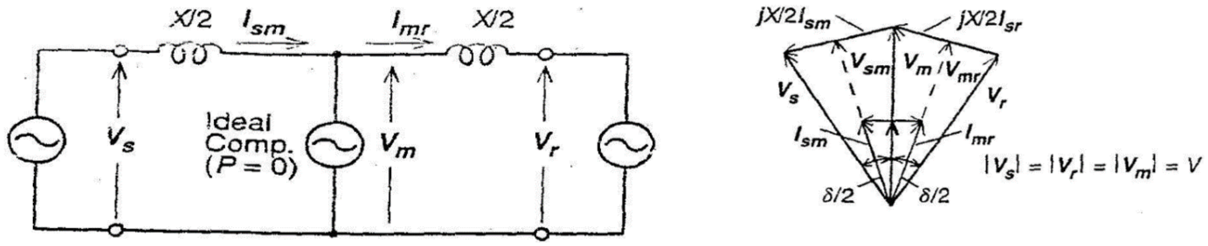
fig.1 (c) (d)

(e)

Diagrams showing some family members of an SVC
Device:(a) thyristor controlled reactor & thyristor switched Capacitor in shunt connection with load 1,2 & 3 on a radial System,(b) thyristor swiched capacitor with a protective Inductive element,L,(c) 3-TSCs in shunt arrangement with a TCR to form a TSC-TCR Composite,(d) an FC-TCR/B_{SVC} lin-ked through a circuit breaker and a shunt transformer,(e) a thyristor controlled or switched reactor (a TSC when $\alpha = 0$)

EXPECTATIONS OF SVC IN ELECTRIC POWER SYSTEM

1. It should be capable of maintaining synchronism with power system at the connected bus at all times, even in a worst perturbation situation .Also , at a momentary loss of system bus voltage, owing to fault emergency, the SVC should be capable of readopting the synchronizing state as soon as the fault is cleared.
2. It should ensure adequate bus voltage regulation to maintain efficient voltage support, improved transient stability, proper power oscillation damping for enhancement of system power transportation.
3. For effective voltage support, the FACTS controller should be installed at the bus where the load is connected; whereas, the midpoint of a very long transmission line should be a good point for localization of the controller, all being for improvement of voltage stability. The later is always adopted in transmission system line segmentation for midpoint voltage improvement. See the diagrams below:



Diagrams showing a power system line segmentation for midpoint voltage support & associated vector diagram

Merit of static var compensator in power system improvement

A good number of family members of SVC equipment have been observed to be very functionally competent in the issue of system reactive power compensation for a greater extent of system improvement. Among some important services they offer, specifically considered for FC-TCR compensator include the following:

1. It renders voltage support at the receiving end of an ac transmission line; thus standing as a functionally acceptable better substitute than a conventional fixed bank of shunt capacitors. In this case ,voltage control across the load is flexibly implemented under a thorough regulation scheme; thus, increasing transmission line stability during load variation.

2. Industrially, its performance in power factor correction is very effective. Plants' operation, under a very high irregular peaks of reactive power demand can be handled with an SVC device in order to increase the power factor of the plant; thus, reducing the voltage fluctuation of the plant to avoid damages and eventual procurement of high operation cost .

3.It offers speedy/fast operational services to electric power system with regard to power network parameter adjustment through thyristor switching control mechanism in order to meet the prevailing system condition. This is obviously profitable under system dynamic situations in which operational response of the compensating element should be a perfect match to the system speedily varying situations.

SECTION II

FIX-CAPACITOR, THYRISTOR CONTROLLED REACTOR (FC-TCR) & THE SVC COMPENSATOR MODELING

A close examination of the functional contribution of an FC-TCR device in a power system through mathematical modeling reveals its system bus voltage improvement possibility. Static var compensator modeling is carried out in this section using a diagram that shows its connection with power system . The FACTS equipment consists of a reactor and a bank of capacitor with two thyristor valves that are connected in parallel but in opposite direction to each other. The device is as shown in fig. 2 (a) below. Fig. 2 (b) shows the equivalent variable susceptance of the device.

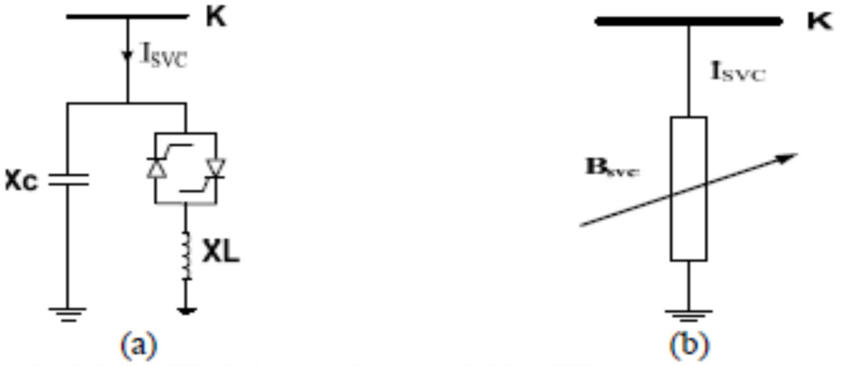


Fig.2 (a) SVC firing angle model (b) SVC total susceptance model

In this modeling, the susceptance , B_{SVC}, is presented as a variable component . The firing angle of the thyristor devices determines the degree of susceptance, B_{SVC}, variation for system bus voltage regulation. Given that the equivalent reactance of the basic circuit is X_{eq} , the shunt connection of the same circuit (ie the SVC circuit) on a given system bus gives the inverse of the basic circuit equivalent reactance(ie $1/X_{eq}$),as the existing equivalent susceptance (Beq) on the same system bus. Therefore,

Xeq = Equivalent reactance of the basic SVC circuit

1/Xeq = Equivalent reactance of the basic SVC circuit in shunt connection to the given system bus

Considering the parallel connection of XC and XL in the circuit, we

Will have,

$$\text{Xeq} = \frac{X_c \,.X_{L\,(\alpha)}}{X_L(\alpha) + X_c} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

But

$$\text{Xc} = -{}^{1}\!/_{\omega C} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$X_{L\,(\alpha)} = \frac{\omega L \pi}{\pi - 2\alpha - sin2\alpha}$$

By substitution,

$$X_{eq} = \frac{-\pi\omega L}{\omega^2 LC - [(\pi - 2\alpha) - sin2\alpha]} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Therefore,

$$1/X_{eq} = \frac{\pi\omega^2\, LC - (\pi - 2\alpha - sin2\alpha)}{-\pi\omega L} \ldots\ldots\ldots\ldots\ldots(5)$$

$$= \frac{(\pi - 2\alpha - sin2\alpha)}{\pi\omega L} - \frac{\omega C}{1} \ldots\ldots\ldots\ldots\ldots(6)$$

Since,

$$1/X_{eq} = B_{eq} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

And $B\text{eq} = B_{\text{L}}(\alpha) + Bc \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$

By matching their corresponding/equivalent variables in equation (6) we have,

$$B_{\text{L}}\,(\alpha) = \frac{\pi - 2\alpha - sin2\alpha}{\pi\omega L} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

$$B_c = -\omega c/1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

Observation:

Equation (9) obviously shows the interdependency among inductive susceptance, firing angle, α, the inductance of the inductor and angular frequency, ω. As a result, any increase in inductance of the reactor will ,conversely, manifest a corresponding decrease in value of susceptance as other variables in the expression are held constant. Similarly, a change in thyristor firing angle, α ,will also reflect on the value of the susceptance as other variables remain constant. However, It is only the delay firing angle of the thyristors that can be conveniently used to effect some changes on the equivalent susceptance in a filed work, since the values of the fixed capacitor and inductor are always pre-determined in design and manufacturing stage of the SVC device.

Legend:

Xc = capacitive reactance of the fixed capacitor, C
XL(α) = Inductive reactance of the reactor, a function of the thyristor firing angle, α.
B_c = capacitive susceptance
B_{eq} = Equivalent susceptance of the static var compensator

Taking the value of real power to be zero (i.e Psvc = o), the power flow equation can be briefly summarized as shown

$$Q_{svc} = -V^2 B_{svc} \quad \ldots\ldots(11)$$

$$= -V^2 \left(\frac{(\pi-2\alpha)-\sin2\alpha}{\pi\omega L} - \frac{\omega C}{1} \right) \quad \ldots\ldots(12)$$

But from transmission line power flow equation,

$$S = P - jQ \quad \ldots\ldots(13)$$

Therefore, substituting for Q_{SVC} from equation(12) as Q in equation (13), we obtain

$$S = P_{SVC} - \left[-jV^2 \left(\frac{(\pi-2\alpha)-\sin2\alpha}{\pi\omega L} - \frac{\omega C}{1} \right)\right] \ldots\ldots(14)$$

Recall that,

P_{SVC} = real power = 0 ; therefore,

$$S = 0 + \left[jV^2 \left(\frac{(\pi-2\alpha)-\sin2\alpha}{\pi\omega L} - \frac{\omega C}{1} \right)\right] \ldots\ldots(15)$$

Where ,

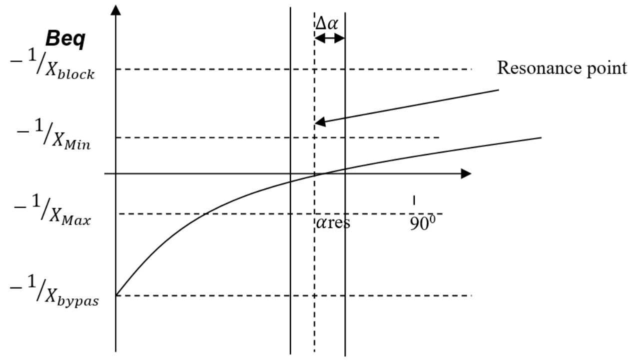
P_{SVC} = SVC real power

S = Apparent power

V is the bus voltage , While Qsvc is the SVC reactive power which is directly proportional to the product of the square of the voltage and the variable susceptance, Bsvc [refer to equ.(11)] .

From the equations, we see the direct proportionality of reactive power of the SVC, to the magnitude of the bus voltage raised to power 2.This means that the adjustment of Bsvc makes a direct impact on the Qsvc; thus, regulating its quantity in a manner in which the susceptance is varied. Beq can be plotted against the the thyristor firing angle, α, defined as the delay angle measured from the crest of capacitor voltage to the firing instant.

Diagram showing an svc susceptance Plotted against the Thyristor firing angle fig.3.0



From the graph, unlike the TCSC counter-part, the SVC does not suffer from the effect of firing angle resonance, αr.The pararell arrangement of the basic module is akin to a discontinued module. As a result, the exempted range within the neighborhood of zero point, along the Beq axis is not accountable. Therefore, the upper and lower limit of the susceptance (i.e $\overline{Bsvc}$ and $\underline{Bsvc}$) make up the total susceptance as depicted on the graph above.

STEADY AND DYNAMIC STATE OF CURRENT-VOLTAGE CHARACTERISTICS OF SVC DEVICES

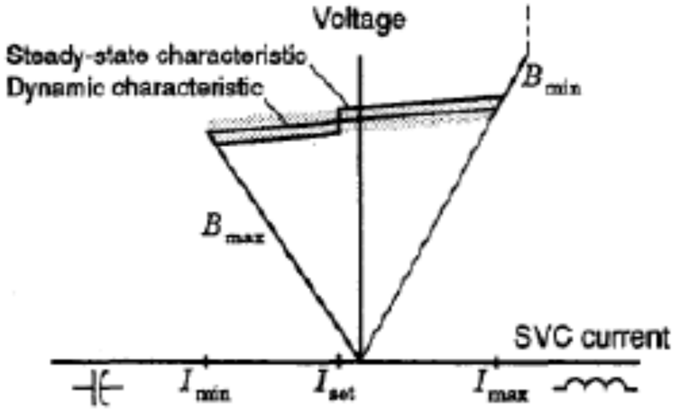


Diagram showing steady and dynamic state of current-voltage characteristics of the SVC fig.3.1

The diagram above illustrates the dynamic and steady state characteristic of current and voltage of the static Var compensator The voltage regulation as shown from the droop is on account of current-reactive power variation through the adjustment of the susceptance within the active control range .The slope of the graph largely depends on the reactive power distribution .At capacitive mode, the static Var compensator functions as shunt capacitor for issuance of QSVC into the system; and as a shunt inductor for absorption of QSVC at inductive mode, all being to maintain the system bus voltages within the acceptable operational limit

SECTION III
EXCHANGE OF REACTIVE POWER BETWEEN THE SVC DEVICE AND THE LECTRIC POWER SYSTEM

As already noted in the diagram, the composition of capacitor and thyristor controlled reactor in the SVC circuit provides an SVC composite of a constant (ie fixed) capacitor, shuntly configured with a thyristor – reactor segment (TCR). The fixed capacitor is designed to issue its inherent reactive power (capacitive) whose quantity to the power network is regulated via the TCR branch for system reactive power compensation.

Functionally, the impart of reactor segment is obtained in absorption of reactive power that is made available by the fixed capacitor as well as that produced by electric power system itself.

As such, when the reactive power for voltage regulation drastically decreases on the system, the thyristor firing angle has to be varied to fully offset some amount of reactive power supplied by fixed Capacitor. Then, in supplying the reactive power for voltage compensation, the firing angle increases to reduce the rate of reactive power intake of the TCR .

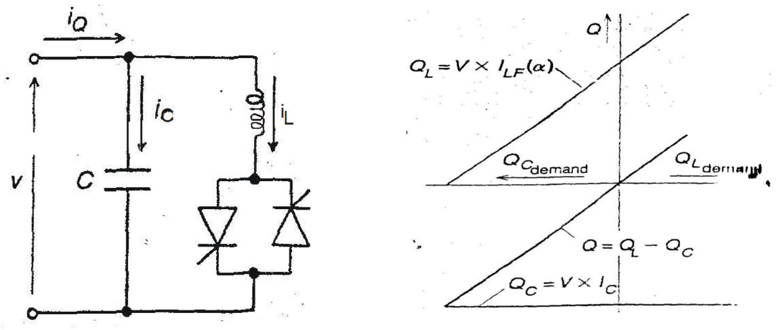


fig.3.2

Diagram showing the FC-TCR device and the graphical relationship of its Var demand and output

This, as a result, causes the availability of more reactive power from the fixed capacitor into the system .When the TCR is switched off completely ,the power system experiences a maximum reactive power ‘’deposit’’ which is equal to the amount at which the fixed capacitor is rated.

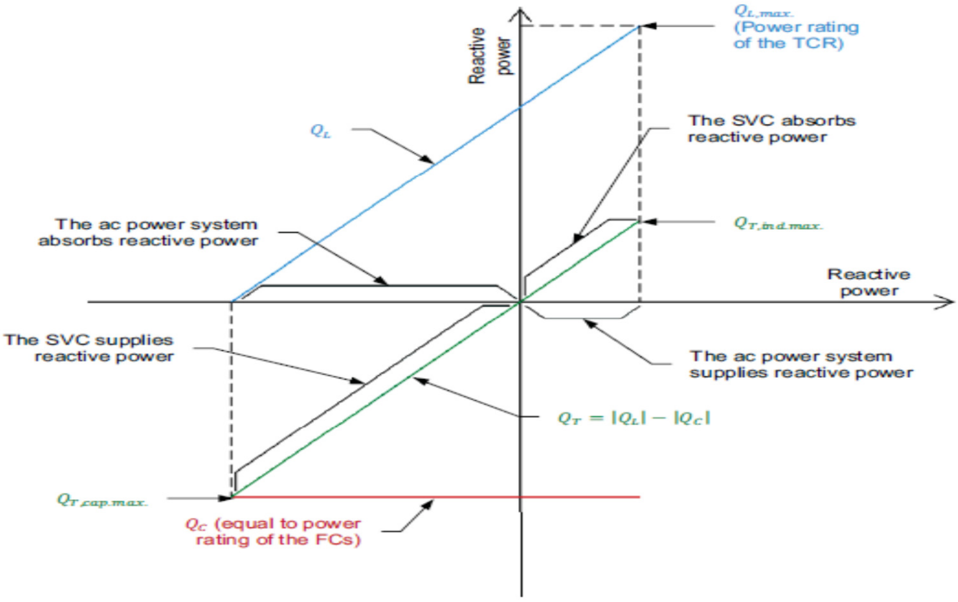


Figure 32. Reactive power exchange characteristic of an SVC of the TCR-FC-type.

On the contrary, in excess amount of reactive power in the system, the TCR should be capable of absorbing, first ,the reactive power due to the fixed capacitor ,and second ,the extra reactive power provided by the system. Under practical application, the TCR is always designed very big in capacity, in order to take care of the above situation; otherwise, if the TCR is only made to account for reactive power due to the fixed capacitor ,it will be extremely difficult to compensate for reactive power generated by the system itself.

Assuming the reactive power (Q_{TOTAL}) rating of SVC capacity is within -200Mvar to +30Mvar range ; then the supposed designed reactive power capacity of TCR component should be 230Mvar to accommodate the range, although at a considerable high cost implication, due to large size. The large size ,of course, in this case, should necessitate the reasons for installing an efficient harmonic filtering device that should take care of the extra harmonics due to increased size of the TCR branch.

In all, the total reactive power exchange by SVC device with the electric power system is equal to the reactive power supplied by the fixed capacitor minus the variable reactive power Q_L(inductive) absorbed by the TCR.

SECTION IV
STATIC VAR COMPENSATOR CONTROL SYSTEM

Given the direct proportionality of system reactive power with the bus voltage on the ground that the reactive power in a power network develops voltage on the system buses, it follows that the two quantities can rise and fall in the same manner and at the same time within the same system. Therefore, knowing the status of one of the two variables, the state of the other variable can be imagined; since the availability of one is the certainty of the other.

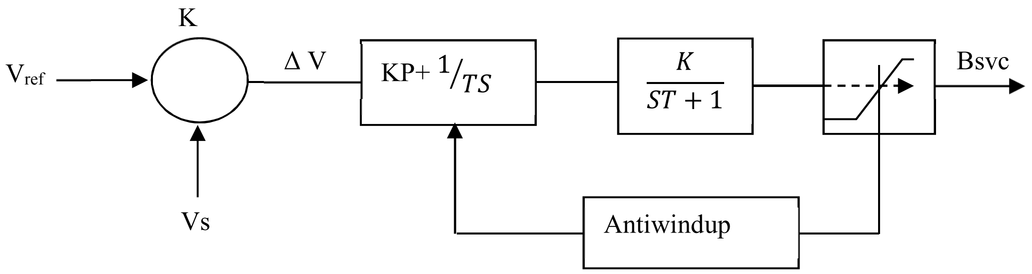


fig.3.3

Diagram showing the control scheme of an SVC device

In the control diagram above, the system voltage sample, Vs and the reference voltage, Vref meet at the summer point, K. A differential voltage, ΔV is being generated which is coupled to the subsequent section of the control unit. It is further processed to produce the right firing angle required to vary Bsvc in order to inject or absorb the reactive power by the static var compensator for the network bus voltage regulation. The control of the firing angles of the thyristor valves with respect to zero crossing of the phase voltage, enables the

SVC device to control the bus voltage magnitude within the required system tolerance. Varying the thyristor angles results in a corresponding variation of the circuit current which generates the quantity of reactive power consumed by the inductor or injected by the capacitor. It is very imperative to know that at firing angle, $\alpha = 90$, the capacitor is fully inserted on the line and the inductor branch completely de-energized for full capacitive compensation ,and consequent bus voltage maximum increase .On the other hand,the inductor is completely activated at $\alpha = 180$,to give room for full inductive compensation impart ,and corresponding minimum voltage decrease of the system buses.

Actually, the firing angle limit, $90 < \alpha > 180^0$ suggests the range of angles within which the thyristors can partially operate as switches. Thus, the progressive triggering of the thyristors within these angular range makes a successive mode of partial switching, obtainable with the power electronic components. This determines the manner in which the equivalent susceptance BSVC is varied with respect to the changing angles, as illustrated in the diagram below

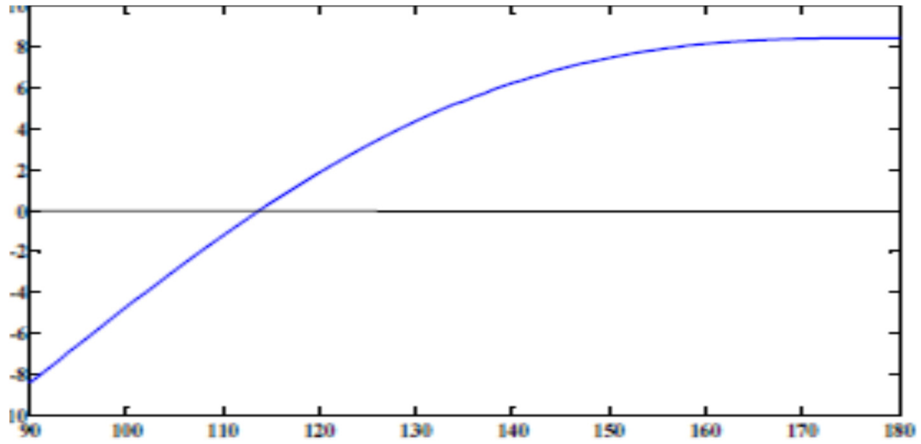


fig.3.5

Diagram showing the variation of B_{SVC} with respect to thyristor firing angle

The extent of participation of capacitor and inductor devices for reactive power injection and absorption on the network, under these varying firing angle range, at the thyristor gate-pulse signal application, is determined by the degree of the thyristors conductivity within this range of angles. By these means, the level of reactive power available for a proportionate level of voltage on the system buses can be met. This explains the adjustment mechanism of the SVC susceptance, in relation to bus voltage improvement in electric power system.

Expectation of the control system: Every responsive and speedy control system (eg PI system) for variation of SVC susceptance should be capable of the following actions:

1.Determination of the quantity of reactive power that must be absorbed by the TCR so as to meet the amount required for adequate voltage compensation in the power system, taking cognizance of the quantity provided by the fixed capacitor.

2.It should control the thyristor firing angle with respect to the rms value of current along the TCR branch such that the amount of reactive power (inductive) to be absorbed will be equal to the quantity absorbable by the TCR.

SECTION V

TCR , ITS CURRENT FLOW AS RELATES TO CONDUCTION ANGLE, σ AND THYRISTOR FIRING ANGLE CONTROL

The possibility of current flow through the reactor element is due to the adjustment of the thyristor firing angle in proportion to the suitable amount that can freely pass through the TCR branch. By this , the reactance of the inductor element can theoretically be assumed controllable from maximum , taken to be at the point of thyristor “full switching-on “ to zero when the thyristor is completely off.

The thyristor “off-switching” is intentionally delayed with respect to the crest of the applied voltage in every half cycle; thus, necessitating the control of the time duration of the current conduction interval within the TCR component. See fig.3.4 below.

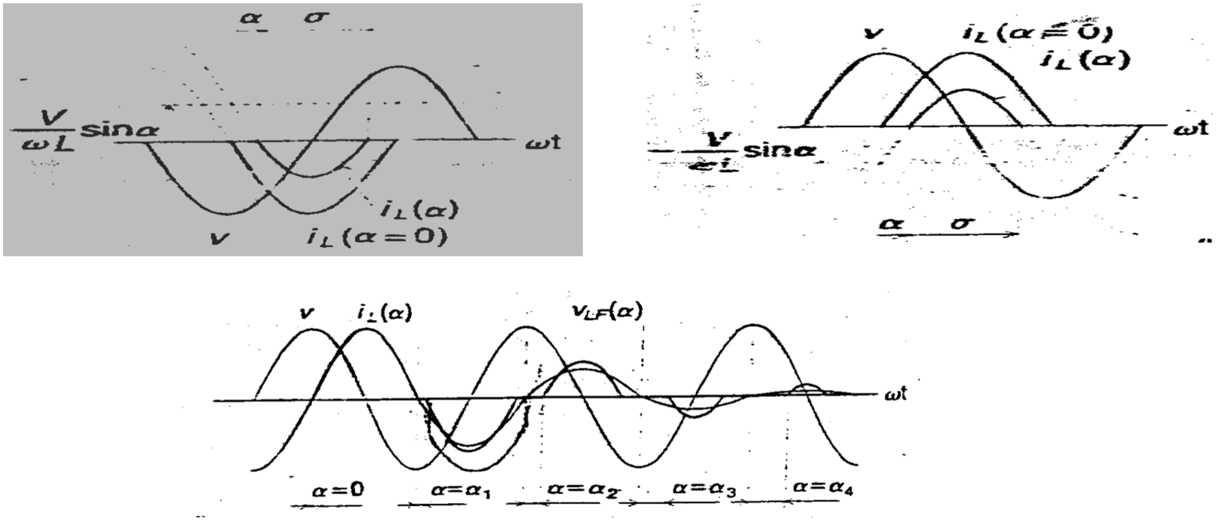


fig.3.4

Diagrams showing the functional effect of thyristor firing delay angle on the system operating waveform

In the diagram , the coupled voltage ,v, and the current through the inductor , i_L (α) at α = 0 (ie upon switch closing) and at arbitrary delay angle ,α are as illustrated. So at α = 0 ,the thyristor switching is accomplished at the crest of the applied voltage .As such ,the flowing inductor current is equal to the amount that flows on the TCR part as the system operates at a steady state when the thyristor switch closes. Considering the thyristor pulse-gate application at an angle, α ,within the range, $0 \leq \alpha \leq 90^0$; with respect to the crest voltage , the expression for current at TCR branch can be derived thus,

Recall that,

$\frac{Ldi}{dt} = v(t)$,(voltage across the inductor)……..(16)

$Ldi = v(t)dt$

$di = 1/L\, v(t)dt$

Integrating the both sides and considering, α and ωt as the lower and the upper limit respectively, we have

$i = 1/L \int_{\alpha}^{\omega t} v(t)dt$

$v(t) = V \cos\omega t$

$i = 1/L \int_{\alpha}^{\omega t} V\cos\omega t dt$

$= V/L\omega[\sin\omega t]_{\alpha}^{\omega t}$

$= V/L\omega[\sin\omega t - \sin\alpha]$ ....(17)

Taking a look on equation (17), above, we see the $^{V}/_{\omega L}\sin\alpha$ fragment, as a thyristor firing angle dependent in which the sinusoidal current at $\alpha = 0$ is offset, Shifting up and down in negative and positive half cycles respectively. Being that the thyristor "switch-off" is attained at voltage zero-crossing, the work of conduction angle, σ control of the thyristor in an SVC device is always achievable. By this, the delay angle, α describes the prevailing conduction angle as $\sigma = \pi - 2\alpha$;and so, the increase in delay angle engenders a corresponding increase in offset, hence, enabling a reduction in conduction angle, σ of the thyristor; and Consequent reduction of the current in reactor branch . As the delay angle, α reaches maximum at $\alpha = 90^0$, correspondingly, the offset-current rises to maximum, $^{V}/_{\omega L}$; and at this point the conduction angle as well as the reactor current becomes zero.

From our discussion, we can accept the fact that the reactor current can be varied using the thyristor angle; starting from maximum value when $\alpha = 0^0$ to minimum value when α is almost 90^0. The graph below illustrates the reactor current $i_L(\alpha)$ in joint with its fundamental segment $i_{LF}(\alpha)$ in various delay angular ranges, α.

It is noteworthy the fact that the variation of the thyristor angle to influence the magnitude of reactor current on the TCR branch can be done once in every half cycle – positive and negative half cycle within the $0 \leq \alpha \leq 90^0$ interval. The magnitude of the fundamental reactor current $i_{LF}(\alpha)$ in relation to the thyristor firing angle can be represented thus,

$I_{LF}(\alpha) = {}^{V}/_{\omega L}\ (1 - {}^{2\alpha}/_{\pi} - {}^{\text{Sin}2\alpha}/_{\pi})$................(18)

Where,

V =Magnitude of the applied ac voltage.

L =Inductance of the thyristor controlled reactor.

ω = Angular frequency of the applied voltage.

A plotted graph of the amplitude variation of $I_{LF}(\alpha)$ current against the thyristor delay angle is as shown below:

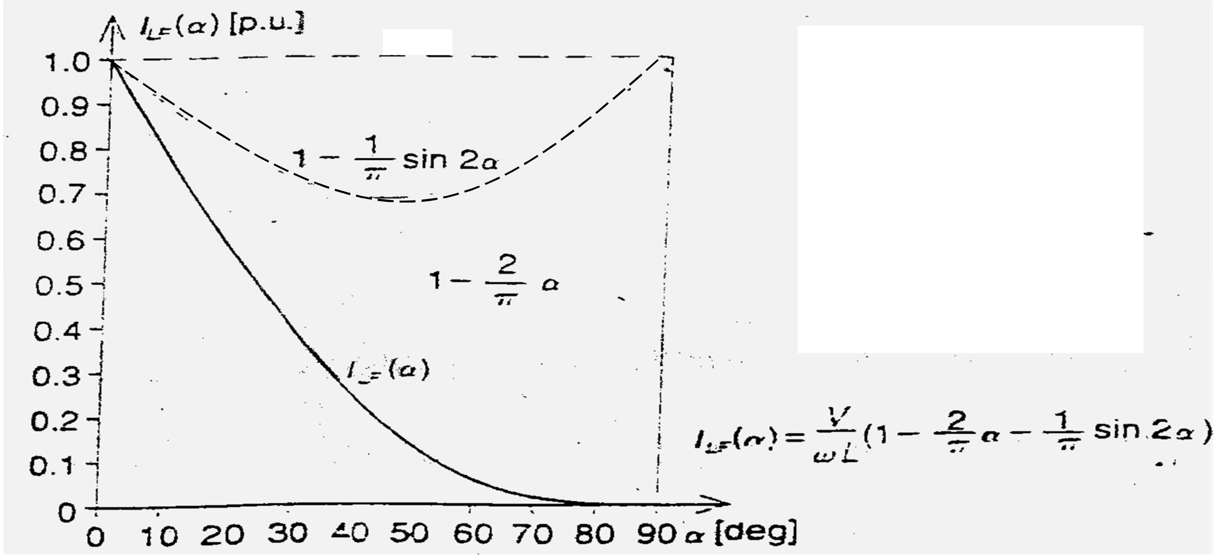


fig.3.5

Diagram showing a graphical relationship of the thyristor firing angle and the reactor fundamental current,$I_{LF}(\alpha)$

From the graph we can see that the TCR has a control over its fundamental current ,$I_{FL}(\alpha)$;starting from zero p.u (ie 0 p.u), when the thyristor is off, to maximum,1 p.u, when it is fully on. In this manner, the influence of TCR over $I_{FL}(\alpha)$ seems as though, it is a variable reactive admittance whose adjustment determines the level of current along the system conductor. We can, therefore, derive the adjustable susceptance of the reactor as shown.

Recall that,

$I_{LF}(\alpha) = {}^{V}/_{\omega L}\ (1 - {}^{2\alpha}/_{\pi} - {}^{\text{Sin}2\alpha}/_{\pi})$, fom equ.(18)

Dividing both sides by V, we obtain,

$I_{LF}(\alpha)\ /V = {}^{V}/{v\omega L}\ (1 - {}^{2\alpha}/_{\pi} - {}^{\text{Sin}2\alpha}/_{\pi})$

But , $I_{LF}(\alpha) / V = B_L(\alpha)$, (from I / v = 1/ Z=(G+ jB) = admittance ,G = 0),

$I_{LF}(\alpha) / V = {}^{1}/{\omega L}\ (1 - {}^{2\alpha}/_{\pi} - {}^{\text{Sin}2\alpha}/_{\pi})$

Therefore, $B_L(\alpha) = {}^{1}/{\omega L}\ (1 - {}^{2\alpha}/_{\pi} - {}^{\text{Sin}2\alpha}/_{\pi})$.........(19)

Where,

$B_L(\alpha)$ = The variable reactor susceptance

α = Thyristor firing angle

ω = System angular frequency

L = Reactor inductance.

Equation (19) shows that the susceptance, $B_L(\alpha)$ can be adjusted to certain values that are proportional to the adjusted firing angles at that instant to supply the corresponding values of the reactor currents along the TCR branch at that particular time. Thus, with $B_L(\alpha)$, the reactor current can be manipulated through the varying influence of the thyristor delay angle on the face of the applied ac voltage.

It should be clearly known that in actual practice in an SVC operated system, the maximum magnitude of the applied voltage and current of the power system can be limited by the design rating of the compensating equipment. As a result, the operation of a practical TCR can be anywhere in the defined V-I area, determinable by the maximum accomplishable suscptance, voltage and current rating as shown above.

SECTION VI

The effect of thyristor firing angles at 90^0, 180 and 0^0 on TCR reactance, X_{TCR}:

Following the functional characteristics of SVC component, the firing angle of the associated thyristor device do exact some effect on the network.With considerable attention on the functional interdependency between the TCR reactance ,XTCR and the angle ,α at system fundamental frequency, the impart of *90^0, 180 and 0^0 firing angles on* the TCR equivalent reactance are illustrated below:

$$X_{TCR} = \frac{\omega L\pi}{\pi - 2\alpha - \sin 2\alpha}$$

At $\alpha = \pi/2$, (ie $\alpha = 90^0$)

$$X_{TCR} = \frac{\omega L\pi}{\pi - 2\pi/2 - \sin 2\pi/2} \qquad X_{TCR} = \frac{\omega L\pi}{(\pi-\pi)-\sin\pi)} \text{ ....(16)}$$

$$X_{TCR} = \frac{\omega L\pi}{0} (\sin\pi = 0)$$

$$X_{TCR} = \infty \text{ … … … … … … … … … … (17)}$$

At $\alpha = \pi$, ($\alpha = 180^0$)

$$X_{TCR} = \frac{\omega L\pi}{\pi - 2\pi - \sin 2\pi}$$

$$xTCR = \frac{\omega L\pi}{-\pi-0}; \text{ for } \sin 2\pi = 0$$

$$X_{TCR} = \frac{-\omega L}{1} \text{ ....(18)}$$

At $\alpha = 0$,

$$XTCR = \frac{\omega L\pi}{\pi - 2(0) - \sin 2(0)}$$

$$X_{TCR} = \frac{\omega L\pi}{\pi} = \omega L \text{ … … … … … .....(19)}$$

From equations (17), (18) and (19), it is clearly seen that TCR reactance is equal to ∞, - XL (ie $-\omega L$) and XL (ie ωL) respectively, showing that the TCR reactance is at infinity when the firing angle α , is tuned to 90^0 ($\alpha = \pi/2$), giving room for full insertion of capacitor for full capacitive compensation on the line .On the same hand, the reactance of X_{TCR} is theoretically equal to $-\omega L$ when the angle is 180 ($\alpha = \pi$) and ωL when it is 0^0.

α = thyristor firing angle
XL = ωL (inductive reactance)
$\sigma = 2(\pi - \alpha)$, (conduction variable)

Therefore, expressing X*TCR in terms of conduction ,σ, we have* $X_{TCR} = \frac{\omega L\pi}{\sigma - \sin\sigma}$*… … … ….(20)*

Note: The parallel addition of XC and XL reactance in an FC-TCR device gives the following effective reactance of the component due to the contribution of X_C and X_L reactance:

$$xsvc = \frac{L\pi .1/C}{[2(\pi-\alpha) - \sin 2(\pi-\alpha)] - 1/\omega C]} \text{ ....(21)}$$

OR

$$xsvc = \frac{L\pi .1/C}{[(\sigma - \sin\sigma) - 1/\omega C]} \text{, in terms of conduction variable}$$

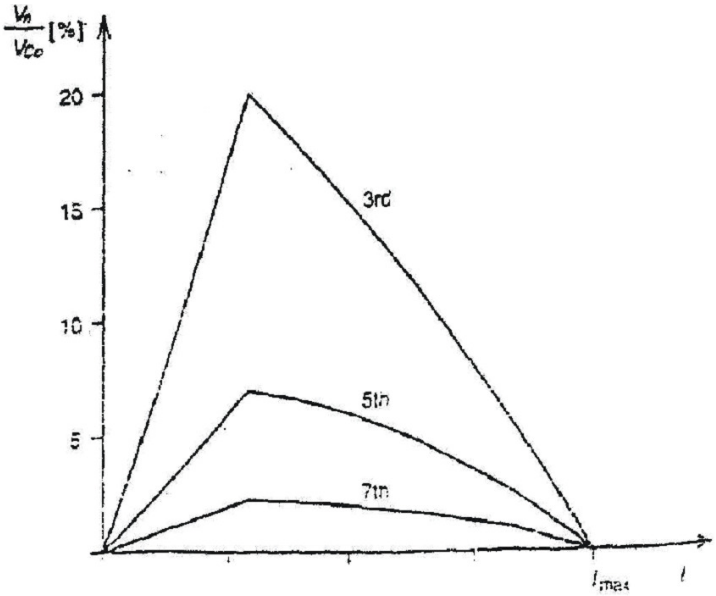
SECTION VII

Harmonic Voltage Generation By TCR compensator:

Despite the obvious benefits of SVC devices in electric system, it has been found that the functions of the equipment has not been without some deficiencies. These problems are anchored on the unwanted quantities that are released into the system, whose wave forms are quite out of the the shape of the original source quantities from which they constitute. These are current and voltage harmonics generated by the TCR component of SVC equipments .The inability of the compensators to receive all the ac source electric quantities to generate a similitude of the received input signal at the output without a significant deformation engenders the possibility of harmonic generation which is a serious matter in power system operation.

With partial conduction of the TCR , the SVC compensators are capable of impacting harmonics into the power system. This is due to the irregular switching on and off of thyristor valves in the course of reactive power injection and absorption, and consequent erratic manner of compensating voltage development within the system . The odd harmonic generated are function of the delay angle, α; and its corresponding voltage from the currents in circuit largely depends on the impedance ratio of the TCR inductor element and the fixed capacitor (i.e. $^{XL}/_{XC}$)

As shown in fig.2.0 below, the odd harmonic voltages – 3rd, 5th and 7th produced in capacitive range are plotted against the system line current, I. The thyristor controlled reactor is considered under the rated compensating voltages against the varying line current. It is very essential to note that the harmonic beyond the 7th order are completely disregarded.



A diagram showing graph of odd harmonic Voltages versus line current

Fig.3.6

For the fact that these harmonics are richly of voltage sources and that the TCSC are usually adopted in a long transmission line with a considerable high impedance, and a relatively low magnitude of line current harmonics; the lower order harmonics which seems to be relatively high in magnitude, may not significantly add to the existing harmonic line current.

Effect of SVC Generated Harmonics on power system :

The harmonics generated by the compensator; though in a relatively lower quantity compared with the generated ambient harmonics, constitutes a part of power network functional defect; following their mix-up and circulation with the normal system variables. Some of these harmonic problems among many others as obtained in electric power network can be stated as shown below:

1. Power losses and temperature increase are always associated with flow of harmonic current in both the thyristor valve and inductor element (i.e. the reactor) of the circuit.
2. The generated harmonic voltages due to the harmonic current as stated in (1) above can cause abnormal increase in voltage as well as a high degree of stress on the SVC component.
3. The harmonics generated, either in current or voltage form is one of the main causes of sinusoidal wave deformation in electric power system.

Method Of Harmonics Control In Electric Power System:

The main component for harmonics production in a SVC compensator is the thyristor controlled reactor (TCR) segment which comprises of two parallel but opposite connected thyristors in series with an inductor element, X_L. These TCR branches generate harmonics quantities which adds to the fundamental current. The harmonics current equation as a function of thyristor delay angle can be expressed as follows:

$I_{Ln}(\alpha) = 4V/\omega L\pi[(\sin\alpha \cos(n\alpha) - n\cos\alpha \sin(\alpha n))] / n(n^2 - 1)$

Where,

$n = 2k + 1$

and k ranges from 1, 2, 3, 4, 5, …

See below the graph plotting of the current harmonic amplitude variation, expressed in percentage, as against the thyristor delay angle, α

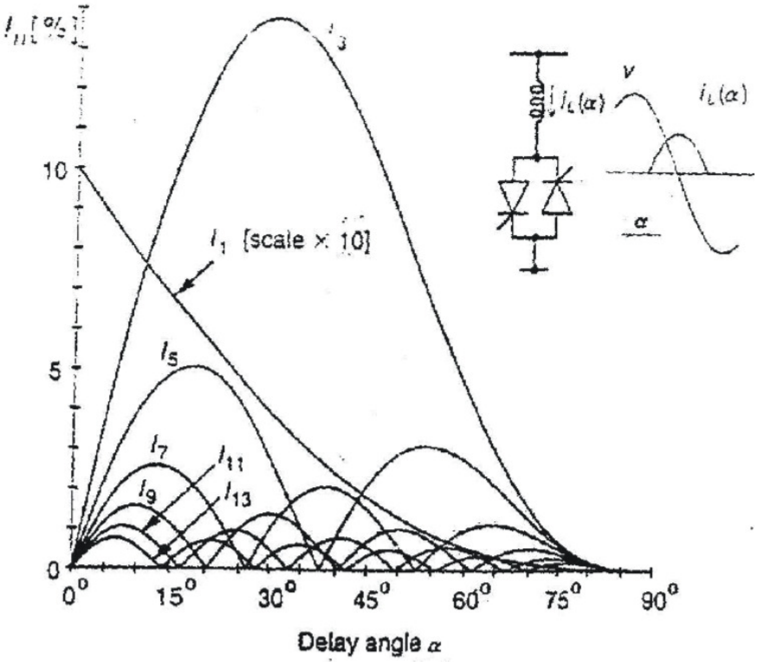
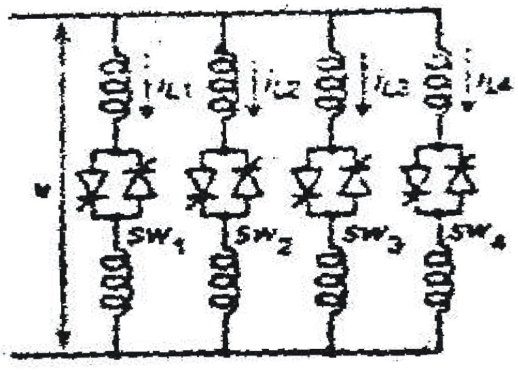


Diagram showing current Harmonic amplitudes plotted Against the thyristor firing angle

Fig. 3.7

The following methods can be adopted to control harmonics generation in an ac power system:
1.Application of m number of parallel – connected thyristor controlled reactors (i.e. TCR) in which the reactors are suitably controlled that only one of the total number of m reactors is controlled via the delay angle techniques; leaving the remaining number of (m-1) reactors either completely on or off based on the prevailing reactive power requirement in the system. In consequence, the amplitude of all the harmonics reduces by total number, m of the TCR components . In this method, the number of the entire TCR components must be greater or equal to 2 (i.e. m≥2 and the rating of each of the m number of TCR must be(1/m)of the overall reactive power rating needed in the circuit).See diagram below.



Parallel configuration of TCRs In ac network for harmonic current control

Fig.3.8

$$i_{Ltotal} = i_{L1} + i_{L2} + i_{L3} + i_{L4}$$

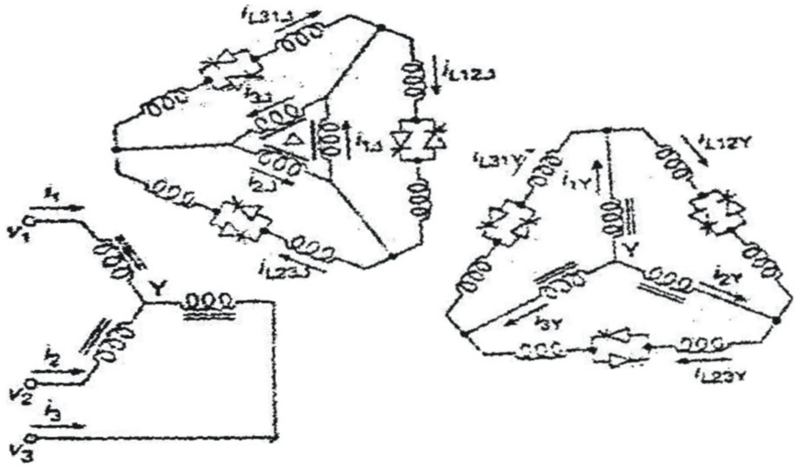
2.Application of 12-pulse TCR configuration in a system can reduce the effect of harmonics. In this arrangement, two uniform 3Φ delta connected TCR are employed ; thus, separating one from Y-connected windings and the other from Δ-connected windings of the secondary of the coupling transformer .

12-pulse TCR configuration

In two uniform three phase,

Delta and wye transformer

Winding for harmonic control fig.3.9



3.Another effective way of checking harmonic occurrence in the system is by maintaning a balanced three phase system under which the triple-n harmonic currents of 3rd, 9th and 15th order can flow in the Δ-connected TCR; in order to divert from the electric power system.

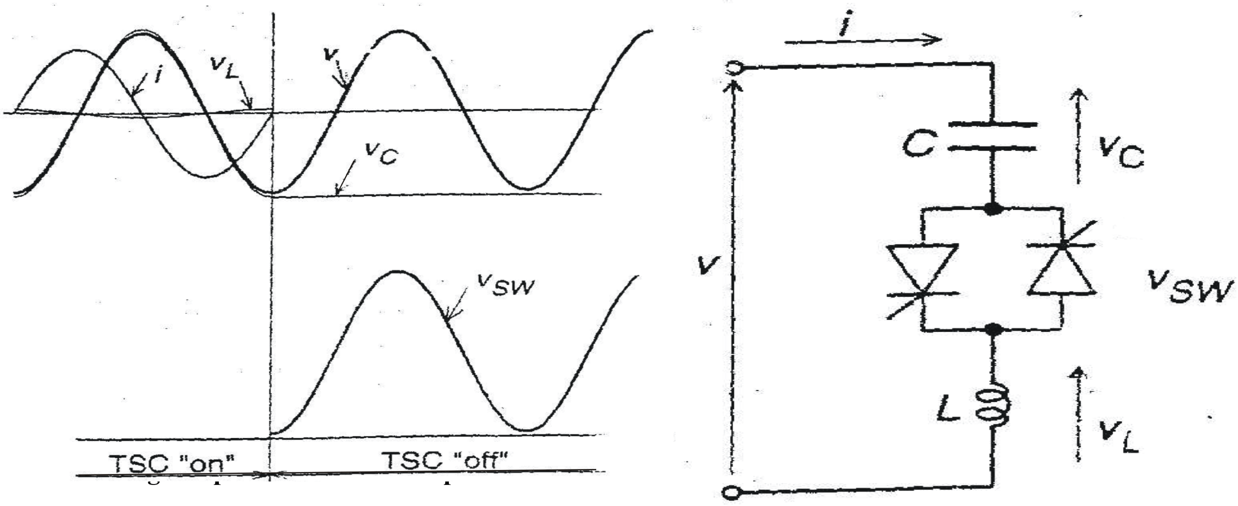
4.Installation of a high pass filter as a means of harmonic elimination can be adopted, in which case ,the reactor of one of the LC filter circuit is shunted with a resistor to enable an appreciable degree of attenuation at higher frequencies, especially, in a case where turned filters fail.

5.Also, a tuneable filter; moreover, at the 3rd order harmonic frequency may be used; more especially, in an occasion of system load imbalance, system oscillation and resonance situations. This has a higher practical application in the modern day system harmonic control.

SECTION VIII

Thyristor switched capacitor (TSC):

Thyristor switched capacitor is among the family members of a Static var compensators that are characteristically shunt connected in electric power system, just as obtained with its thyristor controlled and thyristor switched reactor counterparts (TCR and TSR). The reactance of TSC obeys a step manner variation or zero conduction operation of the normal thyristor switches. In this case, thyistors as ac dependent switches are being used to operate the TSC device in order to switch the shunt capacitor on and off ; without the usual manner of dynamism obtained with thyristor firing angle control. As such, a seemingly step change in reactive power provision is realizable. It is very important, however, to emphasize on the high degree of inflexibility in reactive power regulation using this device due to inability of continuous switching mechanism , unlike in thyristor controlled reactor (TCR).



equipment .Thus,

$$i(\omega t) = [\,Vn^2 / (n^2-1)]\ \omega\cos\omega t \ldots\ldots\ldots\ldots\ldots\ldots(26)$$

$$V_c = Vn^2 / (n^2-1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(27)$$

$$n = {}^{1}\!/\!\sqrt{\omega^2 LC}\text{ , (ie } n = [\,\omega^2 LC]^{-1/2}\text{)}$$

Dividing both the numerator and denominator by $\omega^{1/2}\ c^{1/2}$, the factor n can be expressed thus, n = $\left({}^{1}\!/_{\omega^{1/2}C^{1/2}} \right) / \left({}^{\sqrt{\omega^2 LC}}\!/_{\omega^{1/2}C^{1/2}} \right)$

n = $\left({}^{\sqrt{1}}\!/_{\sqrt{\omega C}} \right) / \left({}^{\sqrt{\omega^2 LC}}\!/_{\sqrt{\omega C}} \right)$,for $\omega^{1/2}$ $c^{1/2} = \sqrt{\omega C}$ ${}^{1}\!/_{\sqrt{\omega C}} = \sqrt{1/\omega C}$, ${}^{\sqrt{\omega^2 LC}}\!/_{\sqrt{\omega C}} = \sqrt{\omega^2 LC/\omega C}$

n = ($\sqrt{1/\omega C}$ /$\sqrt{\omega^2 LC/\omega C}$)

n = ($\sqrt{1/\omega C}$ /$\sqrt{\omega L}$), but $X_L = \omega L$ and $X_C = 1/\omega C$

Then,

n = ($\sqrt{X_C}$ /$\sqrt{X_L}$)

n = $\sqrt{X_C/X_L}$ ……………………………………….(28)

Substituting n = $\sqrt{X_C/X_L}$, into equation (26) and (27), the current and voltage magnitude can be further simplified as

$$i(\omega t) = \left[\left({}^{X_C}\!/_{X_L} \right) / \left({}^{X_C}\!/_{X_L} - 1 \right) \right] V\omega\cos\omega t$$

$$= \left[\frac{{}^{X_C}\!/_{X_L}}{\left(\frac{X_C - X_L}{X_L}\right)} \right] V\omega\cos\omega t$$

$$= \left[\left({}^{X_C}\!/_{X_L} \right) / \left(\frac{X_C - X_L}{X_L} \right) \right] V\omega\cos\omega t$$

$$= \left(\frac{X_C}{X_C - X_L} \right) V\omega\cos\omega t \text{ ………………………(29)}$$

On the same hand, the expression for the voltage amplitude across the capacitor can be written thus,

$$V_C = \frac{X_C V}{X_C - X_L} \text{……………………………………………(30)}$$

Where,

X_C = The capacitive reacance of the TSC device
X_L = The inductive reactive of the TSC reactor
V_C = The amplitude of the voltage across the TSC capacitor
V = Amplitude of the applied voltage
ω = The angular regularly of the system

Switching mechanism:

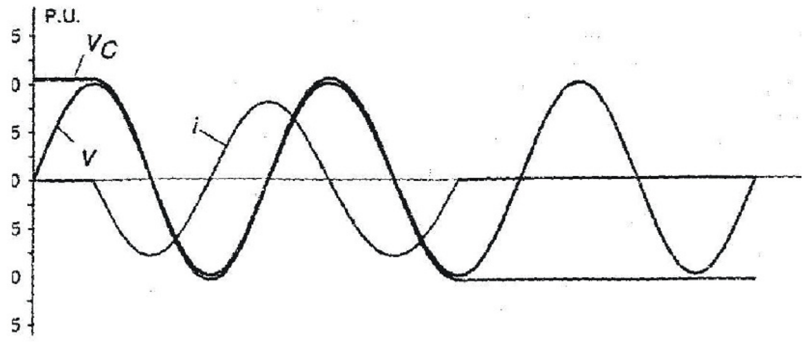
The thyristor switch d capacitor can be switched out at current zero crossing moment, if the pulse at the thyristor gate is removed before this time. The current zero crossing marks the period of peak growth of the voltage across the capacitor; and if the capacitor remains switched out, it will continue remaining charged at the peak level, thus causing the voltage across the non conducting thyristor switch to vary between zero and peak to peak value of the applied ac voltage . See the diagram below

The constancy of the switched out capacitor voltage can necessitate switching in of the TSC at the peak of the applied ac voltage in absence of transient signal as shown in the diagram below.

However, the capacitor bank is usually freed from charges after being switched out, and so, allowing switching back at capacitor residual voltage which exists between zero and Vc. The possibility of this is within a least transient disturbance, if switching on of the thysristor can be done within such a time in which the residual voltage from the capacitor and the applied ac voltage are of the same magnitude.

fig.4.1

Diagram showing the TSC switching in absence Of transient quantities with
Capacitor,Vc Charging fully at current zero crossing



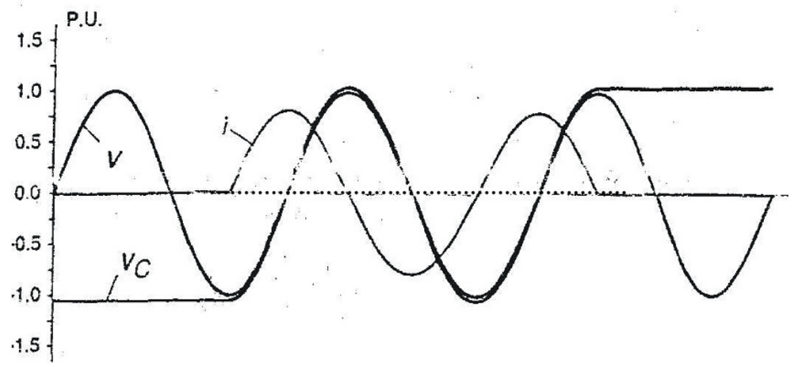
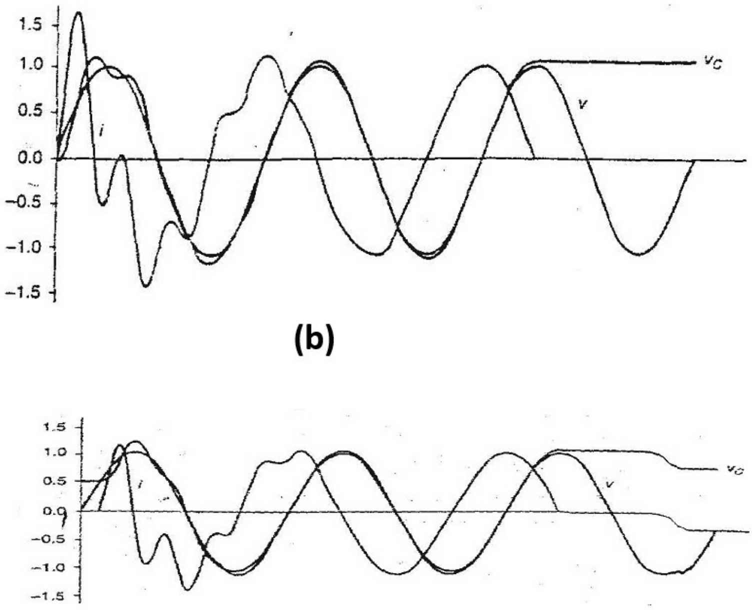


Fig.4.2

Diagram showing the switching manner of a TSC in transient free condition with capacitor, Vc fully charged throughout the period a full cycle

Transit development in thysristor switched capacitor:

Transient signal in a TSC device is due to the development of non-zero $^{dv}/_{dt}$ ac components that results a sudden current surge in the capacitor at the moment of circuit switching .This is an instantaneous value of a steady state capacitor current experienced by the device at the time of switching .The effect of the functional relationship between the capacitor and the current limiting reactor element in conjunction with a damper (ie a small resistor element) results the oscillatory transient obtained in the current and voltage waveforms.



(b)

(a)

Fig.4.3

Diagram showing the transient Waveforms accompanying the TSC switching as the device is fully switched on in (b) and partly Switched on as demonstrated in (a)

Following the problematic nature of transient in power system, a safe period of switching the device to avoid any possible danger to power system is remarkably important. The highest obtainable switching delay period for the capacitor is a full cycle duration, meaning a periodic space of one positive or negative peak, to the next. This stands that the energization of the capacitor must be within any convenient instant of a cycle in which little or no transient is available in the TSC device .With such a time-able and predictable mode of switching, it is obviously certain that a strict application of thysristor firing angle control may not be out- rightly plausible. As a result, the TSC equipment only makes a step-wise change in the reactive current that flows through it which varies linearly with the ac voltage in a habit of the inherent admittance, B_C of the capacitor. See the Diagram below

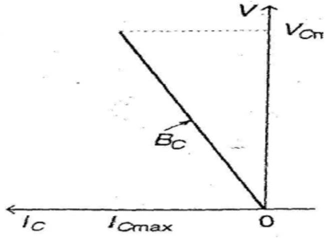


fig.4.4

Diagram showing the V-I character-Istics of a TSC device

Necessary conditions for capacitor transient free switching.

1. The capacitor switching can be preferable at the time when the instantaneous ac voltage is equal to the capacitor voltage. At this point, the peak ac voltage, V must be higher than the l capacitor residual voltage ,Vc.
2. The switching can also take place at the peak of the ac voltage in which the thyristor voltage is least. In this case, the capacitor residual voltage must be equator or higher than the peak ac voltage.

SECTION IX

Thysristor switched capacitor, thysristor controlled reactor (TSC-TCR):

The aim of reducing losses and accomplishing flexibility in dynamic compensation of power transmission system can be reached in proper arrangement of the two or more SVC devices in parallel configuration as shown below. For a certain level of capacitive reactive power output in the power system, a given number of TSC devices say M, can be shunted with one TCR device engaged for output control. The number, M of the TSC devices can be practically determined, taking note of the operation rating of such quantities as voltage magnitude, maximum Var output, current rating of thysristor switches and the cost of system bus installation.

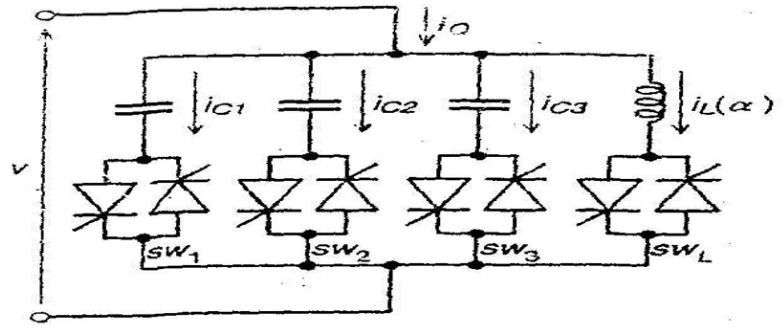


fig.4.5

Diagram showing the basic

Structure of a TSC – TCR device

Similarly, the number of the branches can be expanded to increase the level of reactive power (inductive) as required by the system .

Operational Mechanism: The total outputs power is put into m-divisions, corresponding to m- intervals, each of which a unit TCS component is assigned. For the first interval of the m- divisions, the Var output of the device is controlled from zero to Qcmax/m range, with Qcmax being the total value of reactive power provided by all the TSC branches put together. At this stage, one capacitor bank in the set of TSC group can be switched on through its associated thyristor valve (eg. SW$_1$). A simultaneous switching of a TCR is done using a properly determined firing angle in order that the sum of the reactive power of the TSC and that due to TCR will supply the required amount of reactive power (output) in the system.

For the 2nd, 3rd through to m- intervals, the controlled reactive power output of the system can be illustrated as shown:

Qcmax/m ___ 2 Qcmax/m
2Qcmax/m ___ 3 Qcmax/m
3Qcmax/m ___ 4 Qcmax/m
4Qcmax/m ___ 5 Qcmax/m
(m-1) Qcmax/m __ Qcmax

This is carried out by sequential triggering of the thysristors of the 1st capacitor , 2nd, 3rd, 4th, 5th up to m capacitors of the corresponding TSCs and simultaneously applying the TCR to absorb the excess capacitive reactive power. Owing to the fact that the capacitor banks is subject to switching in and out within one cycle of the ac voltage, the surplus capacitive power in the system, out of the total reactive power output in question should be confined within the limit of one capacitor bank capacity. This necessitates the need for installing equal capacity rating of the connected TCR with the TSC, to enable proper account of the surplus Var on the system. In reality, the TCR device is designed to be lager in capacity than the TSC so as to provide sufficient overlap for the two possible switching conditions.

Var demand versus Var output Characteristics:

From the graph below, a stepwise change of the capacitive reactive power, Q_c is initiated by the thyristor switched capacitor, almost equal to the amount of reactive power demand, Q_d in the power circuit , with net excess capacitive Var and relatively small inductive reactive power output of the TCR. The inductive reactive power, Q_L is applied for cancellation of excess capacitive reactive power .With this, the arrangement can be akin to a peculiar type of fixed capacitor thyristor controlled reactor, in which case, the inductor rates very small and the capacitor charges in discrete-step-like manner to allow the TCR operate in a tolerable control range.

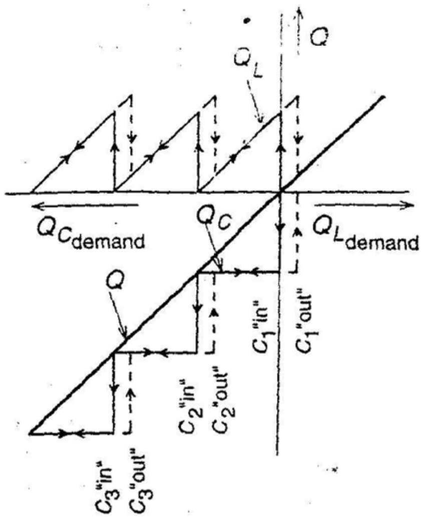


fig.4.6

Diagram showing the graph of Var demand and Var output of a TSC – TCR device

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