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A review of the functional and analytical characteristics of thyristor controlled series capacitor (TCSC) in electric power system.

Nwozor O. E. and Olumoko O. E.

Department of Electrical and Computer Engineering, Federal University of Technology, Minna, Niger State, Nigeria.
Hydraulic Equipments Development Institute, Kumbotso, Kanu State, Nigeria
Corresponding Author's Email: eugenenwozor@yahoo.com; Olumoko_eric@yahoo.com

Abstract

In this work, consideration is solely laid on functional characteristic of Thyristor Controlled Series Capacitor (TCSC) in electric power system. Several operational characteristics of TCSC in electric power system are revealed. The thyristor based controller is modeled to show the various variables that constitute its adjustable reactance, X_{TCSC} and their manner of functional dependency upon one another. With a properly presented graph, the relationship between the thyristor firing angle and the TCSC equivalent reactance are illustrated, thus, showing the two important regions- capacitive and inductive regions, and their extent of restriction with respect to the existing resonance angle, α_r. From the graph, several operational modes of the device are explained as it affects the variability of the TCSC reactance in relation to the thyristor firing angle. TCSC control scheme as well as the mutual interactive response of Flexible Alternating Current Transmission System (FACTS) equipments, in general, is looked into; pointing at four effective FACTS localization Techniques that give room for cordial functional combination of FACTS implements on a system .The characteristics impact of the TCR segment of TCSC is shown, taking a look on the deformed current - voltage waveform outputs of the thyristor controlled series capacitor as generated by its TCR and capacitor branches into electric power system .This is considered under a steady state condition and within capacitive and inductive mode. With Laplace transform, the deformed current and voltage waveforms are derived, analyzed and represented in a skeletal form. Compensating voltage versus current characteristics is examined and explained with well defined diagrams. Lastly, the effect, merit and demerit of the TCR branch of a TCSC circuit are highlighted as relates to the size of the branch (TCR). This branch (TCR) is the major power controlling center of the TCSC device. It is constituted of the Thyristor component which is the switching organ of the compensator for swift response to system frequent phenomenal load changing behavior: a common factor for which the commonly used static Var compensators such as capacitors, reactors etc will soon be relegated .The paper deeply recommends the need for application of the FACTS implement in the modern power technology. This as an emphasis finds roots on the ease for system parameter controllability (using the device)with effect to proffering flexibility in the face of managing system load flow dynamism in modern electricity industry.

Keywords: Characteristics, Evaluation, Functional Review, Power System, TCSC.

1. Introduction

Flexible Alternating current transmission system has revolutionized our contemporary day's electricity industry. Power system is becoming easy to manage owing to the possibility of using FACTS devices in elimination of some adverse situations that have been imposing difficulties on the system.

Electric power system is naturally composed of line parameters and these parameters, as vital system components, determine the operational status of the network, both in dynamic and steady state condition. Therefore any impact on them reflects on the overall activities of the network to influence the system position with respect to determination of the system voltage profile, current magnitude, power phase angles and the system operational capability at large.

As a result, FACTS controllers have emerged very useful for such a system operation, being that their control and manipulation of line parameters are practically feasible for optimum utilization of power generation, transmission and distribution services at the consumer end [4].

The reactance of a system can be adjusted to determine the level of power flow along the line. On the same hand, susceptance at a given system bus can be varied in order to regulate the magnitude of the system bus voltages [5]. To meet such urgent need of power system, especially, during network contingencies, the adjustment of these variables is a matter of speedy response to enable a quick modification and coordination of the parameters so as to obtain suitable values, commensurable to immediate requirement of the network in order to restore the system stability [7] .And such a high speed of response is conveniently found in FACTS concept application.

1.1. Work format

In this work, thyristor controlled series compensator (TCSC) is modeled with the basic circuit that shows the essential components which constitute the device. The interdependency among the inherent variables such as the capacitive and inductive reactance (X_C and X_L) as well as the firing angle (α) of the two parallel and anti-directionally connected thyristors is revealed .The parallel addition of the two reactance produces the equivalent reactance, Xtcsc. These are seen in section 1. Section 2 covers the control scheme for TCSC and briefly discusses the impact of the mutual interaction of FACTS controllers in a system. The waveform characteristics of current and voltage of the series line capacitor and the TCR under a steady state in inductive and capacitive modes are treated in section 3. We see in section 4 and 6 the discussion of voltage – current characteristics as obtained in a TCSC device. Section 5 considers the derivation and analysis of deformed series capacitor voltage, AC line current and deformed TCR current of a TCSC in electric power system using Laplace transform techniques.

2. Modeling of thyristor controlled series compensator (TCSC).

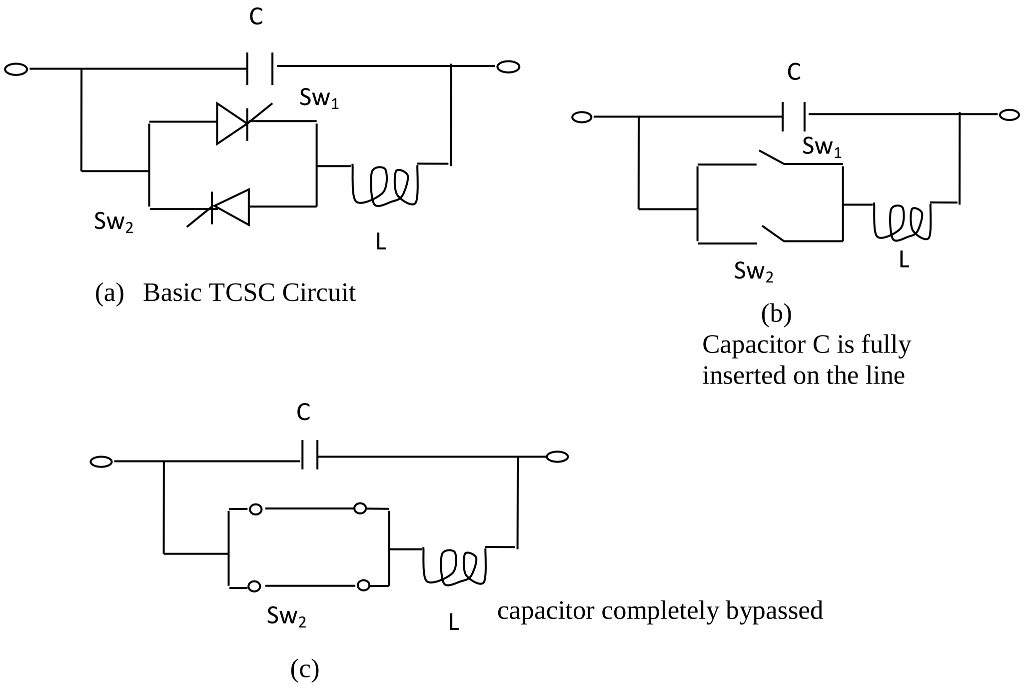


Fig. 1 Diagram showing different modes of TCSC circuits

To look into the functional characteristics of a TCSC component, a good model of the FACTS device is necessary with some mathematical equations that express the interdependency of the natural variables embedded on the expressions that produces the adjustable equivalent reactance. TCSC is formed out of a fixed bank of capacitor, C and a reactor, L with two opposite and parallel connected thyristors of a firing angle, α [1]. The extent of line compensation is owned to the thyristor valve control through the manipulation of the firing angle, under the application of pulse signal at the thyristor gate [4]. This emphasizes the variability mechanism of the accomplished equivalent reactance, Xeq The circuit is duly connected in series on the line to generate the voltage which is in series with the line and in quardrature with the line current .This, in effect, enhances power flow in electric power system.

The diagram above illustrates the compensation modes of the TCSC circuit in relation to the functional characteristics of the capacitor and inductor components through the thyristor switches .Figure 1.0 is the basic circuit of the thyristor controlled series capacitor.1b shows the complete insertion of capacitor, c for full capacitive compensation as the thyristor switches go off completely .This, in effect , causes all the line currents to pass through the capacitor component for its full compensative effect on the line. In 1c,the line current bypasses the capacitor through the inductive branch, and the extent of the compensative action, in this case, depends on the degree of current magnitude allowed to flow through the reactor as determined by the thyristor switches [1,4].

At $\alpha=0^0$, the reactor is energized and the capacitor is bypassed by the line currents via the inductor branch until $\alpha = \alpha_{Llim}$ where the full inductive compensation is felt on the line. It is de-energized at $\alpha=90^0$;hence ,allowing current through the capacitor component on the line [4]

.As such, the only easy route for current passage is through the line capacitor, and so, a capacitive compensation is felt on the line and fully felt when $\alpha = \alpha_{Clim}$ .Therefore, the feasibility of line series compensation with TCSC lies within the inductive and capacitive regions; and within these regions, it is possible to regulate the level of power flow as could be required by any system prevailing conditions provided the resonance angle, α_r is avoided in order to avoid system oscillation[5,4].

The relationship existing among the equivalent reactance, X_C, X_L and the thyristor firing angle,α can be shown in the following equation:

$$Xtcsc = \frac{Xc.X_L(\alpha)}{Xl(\alpha) + Xc} \quad (1)$$

where,

$$Xc = -\frac{I}{\omega c}$$

$$XL(\alpha) \quad = \frac{\omega L\pi}{\pi - 2\alpha - sin2\alpha}$$

$$X_{tcsc} = \frac{-\pi\omega L}{\omega 2Lc - (\pi - 2\alpha - Sin2\alpha)} \quad (2)$$

Xc = capacitive reactance of the fixed capacitor bank, C

$X_L(\alpha)$ = inductive reactance of the inductor, L

X_{TCSC} = Equivalent reactance of the TCSC

α = firing angle of the thyristor valve

Equations (1) and (2) above give the parallel combination of capacitive and inductive impedance, $X_c$and X_L respectively; at a steady state and at the power system fundamental frequency. At this state, the impedance of TCSC constitutes a mere parallel LC circuit with a fixed capacitive and adjustable inductive impedances, X_C and $X_L(\alpha)$. The inductive impedance is a function of thyristor delay angle, α ; defined as the angle measured from the crest of the capacitor voltage.

With the aid of TCR branch, the entire TCSC composite forms a tunable parallel LC component structure to a sinusoidal current wave flowing on the ac line. The TCSC increases the degree of its capacitive compensation on the line from its minimum value, $X_{TCSC\ (min)} = X_C = 1/\boldsymbol{\omega}C$. Then, continuous until parallel resonance when the fixed capacitive value is equal to the amount of the adjustable inductive impedance, $X_L(\alpha)$ obtained at that instant,(ie $X_C = X_L(\alpha)$) [5]. In this case, the maximum X_{TCSC} is reached which is theoretically assumed to be infinity. Any further reduction of X_{TCSC} from maximum will, at this point, make the impedance inductive and attain its minimum, $[(X_C.X_L/(X_L-X_C)]$ at $\alpha = 0$.

Meanwhile, in normal configuration of a TCSC circuit with inductive impedance designed smaller than the capacitive impedance, the variable compensator obviously adapts two working conditions with reference to the internal resonance circuitry[4]. These conditions designate two different operating bands within which the compensator functions outside resonance bound. These are capacitive and inductive region where-in the TCSC impedance, X_{TCSC} are respectively variable within the range , $\alpha_{Clim} \leq \alpha \leq \pi/2$ and $0 \leq \alpha \leq \alpha_{Llim}$

2.1. Graphical illustration

The relationship of the equivalent reactance in the equation above with the thyristor firing angle can, therefore, be better illustrated with a graph as shown below. From the graph , it is clearly seen that the performance of the TCSC is narrowly limited at the resonance point where angle α is equal to resonance angle, αr [4,5] .Thus, for effective operation, a small length of angular distance, Δα must be maintained from the resonance point in order to obtain a maximum and minimum reactance (X_{ma} and X_{mi}) at the equivalent reactance, Xeq axis .The existing operational modes of the thyristor controlled series capacitor (TCSC) can be treated from the graph as shown below.

The graph showed the dominant regions of the capacitive and inductive reactance, the thyristor firing angle, α as plotted against the equivalent TCSC reactance; as well as the several functional modes assumed by the thyristor controlled series capacitor during operation. Such modes as inductive boost mode, capacitive boost mode, bypass and the blocking mode are all explicitly discussed below.

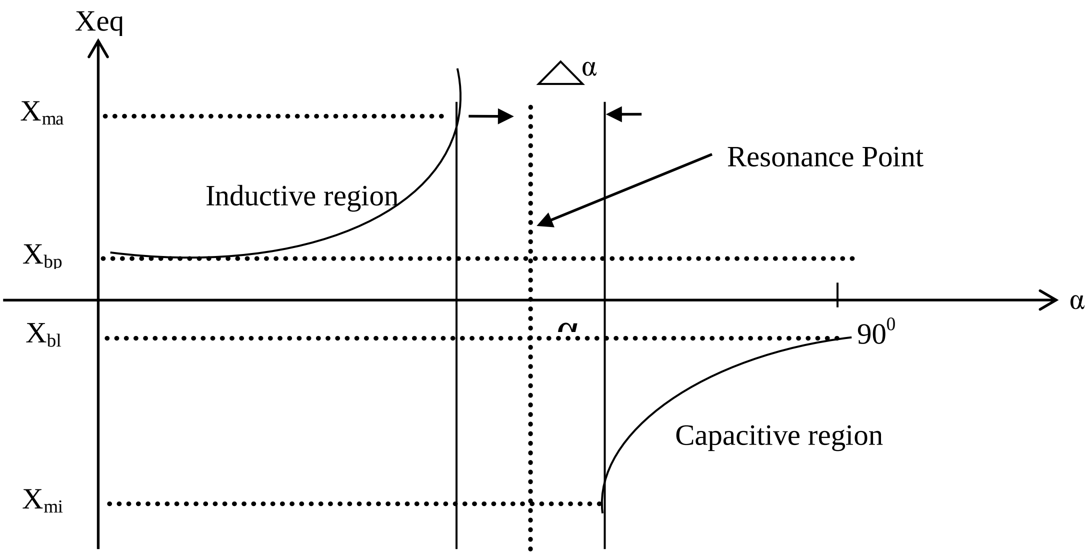


Fig. 2: Diagram showing a plotted graph of X_{eq} against the angle,α

Bypass mode: In this mode, the firing angle of the thyristor valve equals Zero (i.e α= 0),and the circuit behaves as though the L,C components are connected in parallel.

Inductive boost mode: the firing angle, α is greater than zero but lesser than the resonance angle, (i.e. 0^0< α< αr), thus, resulting a plane where the equivalent reactance, X_{eq} is positive and inductive in nature.

Blocking mode: At this mode, the thyristor firing angle equals 90^0(ie α = 90^0), the thyristor becomes non-conductive; as such the full impact of the fixed capacitor is felt on the line for full capacitive compensation capacitive boost mode: for this mode, angle α is greater than the resonance angle, but lesser than 90^0 (i.e. αr <α < 90^0); as a result the equivalent reactance is negative and capacitive [4].

3. The Thyristor Controlled Series Capacitor Control Scheme

Owing to instantaneous occurrences and fast behavior of system contingencies as well as the frequent changing trend of load demand, an active monitoring device with a matching control speed are being installed in the system to man the network control operation[2]. This gives a commensurable variation of the TCSC'S reactance in accordance with the level required by the system for compensation. A good example is a PI control unit[5]. As shown in the diagram below, the TCSC reactance, Xtcsc is the output of the PI controller with P_r serving as a comparable quantity of power fragment with the reference power, Pref. To determine the differential input signal ΔP(ie the error signal), the two quantities (Pr and Pref) are electrically combined at the summer point. Passing the subsequent stages of the control unit, the input signal (ΔP) is eventually processed to generate the angle,α which decides the suitable value of the equivalent reactance required for reactive power compensation [4].

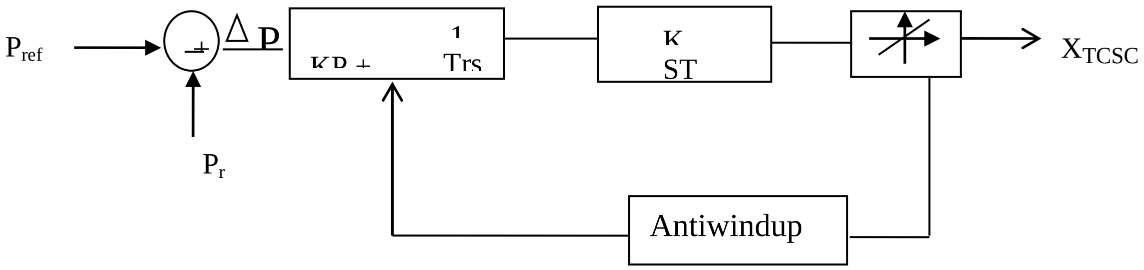


Fig. 3 Diagram showing TCSC PI control Scheme

3.1. Mutal Interactive Response Of Facts Devices In Power System

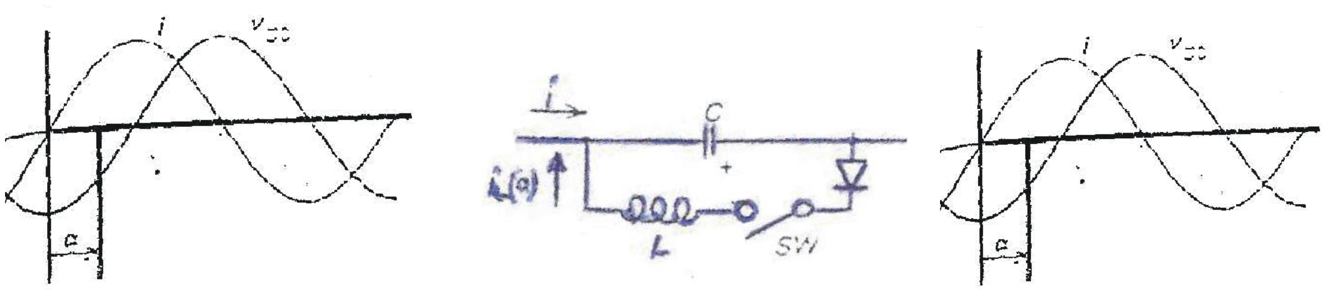
As it is profitable to install FACTS controllers in a system, it is also very important to consider the mutual response of each of the controllers in their respective positions within the system [5, 4]. Since in all the system locations, the expected function from the devices are such that supposes to enhance the operation of power network in order to maintain optimum power flow so as to actualized maximum power transfer, still, the aim as hinted may be eluded if proper attention and essential FACTS localization techniques are not adopted. This usually results from the counter – effect of the equipments' operation, as they independently work to actualize system objectives in their various places of connection [4].To achieve efficient localization of FACTS components, the following techniques can be employed:

a. Jacobian Based Sensatory Method
b. Optimization and Artifial Intelligence Techniques
c. Non – Jacobian Based Techniques
d. Eigen – Analysis Based Method.

4. Current/ voltage waveform characteristics of the capacitor and tcr of a tcsc compensator, considered under a steady state and within the capacitive and inductive mode.

4.1. Capacitive Mode Consideration

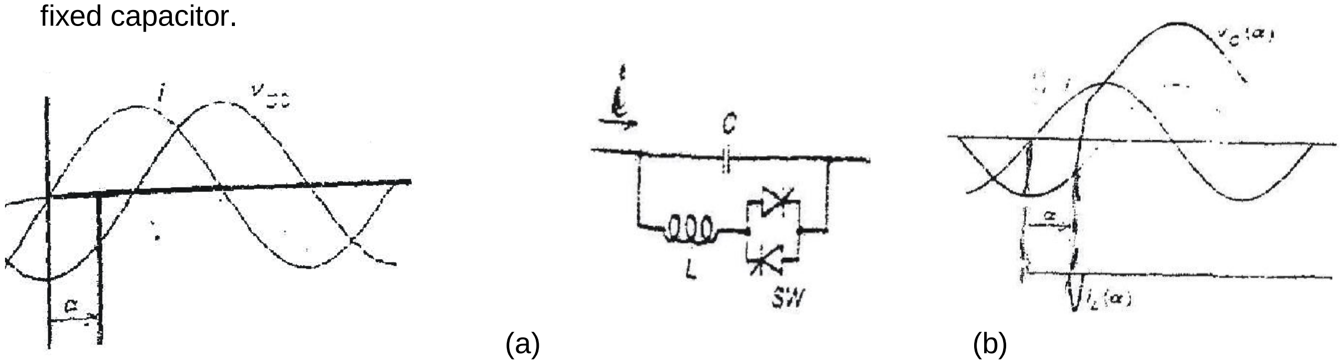
The ac current and voltage wave form modification by the parallel connection of TCR and the fixed bank of capacitor in the TCSC device demands attention in consideration of the equipment installation in an AC system. The sinusoidal wave form of both the two electrical quantities (ac current and voltage) are actually deformed under the functional interaction between the two TCSC components (ie. TCR and C). As a matter of fact, this work extremely looks at the actual operational features and the dynamic expressions of the composite TCSC compensator with respect to observing the impact of the changes in electric system reactive power compensation, following the existence of these deformed waves.



(a) ***(b)*** ***(c)***

Fig.4: Diagram showing (a) TCSC input Voltage and current (b) the TCSC Device (c) output TCSC Voltage and current

Considering fig.1.3 above ,the inductor branch is open through the switch, SW (thyristor valve is assumed off); and the line current , i produces the voltage, v_{co} across the series fixed capacitor.



(a) (b)

(c)

Fig. 5: Diagram Showing the graph of TCSC (a)normal AC input voltage – current wave form and (c)deformed output Voltage - current wave form

When the switch is closed at the instant of turning on the thyristor at an angle , α as shown in figure 5b above ,the capacitor voltage is negative and the line current positive[5].The current now charges the capacitor in the positive direction. This gives a brief explanation of the generated output signal of figure c as the input of figure 5a passes along the line through the TCSC circuit of figure b .At the first half cycle and the subsequent half cycles, the thyristor works like a switch that closes at the delay angle ,α with a diode that is connected in a suitable direction to disallow the TCR conduction as the current crosses the zero point.

At the point of switch closing, there are two different situations that occur : 1. the currents along the ac line keeps discharging and charging the capacitor, 2. The charges on the capacitor reverses at the resonant half cycle of the LC circuit formed as the thyristor is fired.

From the initial half cycle at which the thyristor is fired, a dc off-set is generated by the resonant charge reversal[4]. In this case, the subsequent dc off-set for the next negative half cycle can be reversed through by maintaining the same firing angle,α ,As a result, a voltage wave form , symmetrical about the zero axis is obtained. Thus , the above details can be better understood with the diagrams below

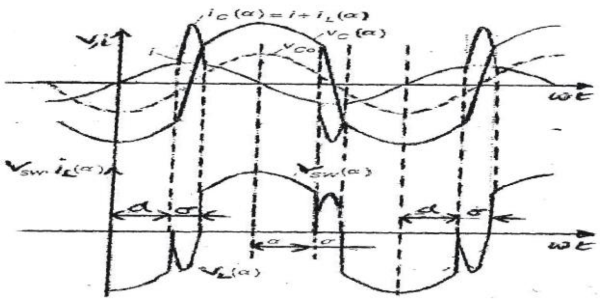


Fig.6: Diagram showing the deformed TCSC capacitor voltage, current, generated, dc off-set and the generated reversed charge.

4.2. Inductive Mode Consideration

In a real operation, the TCSC is functionally controlled through reversal of capacitor voltage whose time duration does not only depend on the magnitude of the line current but also on the inductive to capacitive reactance ratio, X_L / X_C [1,4]. In a situation where the inductive reactance is very much more greater than its capacitive reactance counter-part, instantaneous voltage reversal occurs which periodically generates a sequence of square wave across the capacitor and this is added to the sine wave which is produced by the line current [6].

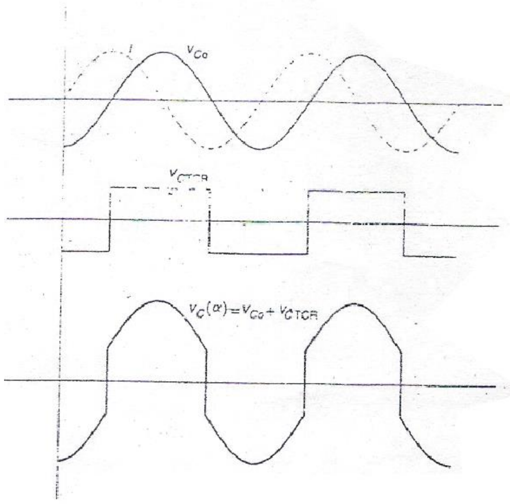


Fig. 7: Diagram showing the TCSC Controlled and uncontrolled voltage components (Vco and Vctcr) as well as the deformed compensating capacitor voltage

As shown in fig.1.6,the steady state compensating voltage across the series capacitor consists of two components: the controlled and uncontrolled components[4]. The uncontrolled component , Vco is the sine wave whose magnitude is in direct proportionality with the amplitude of the existing line current while the controlled component ,V_{CTCR} is the square wave whose magnitude is controlled via the charge reversal by the TCR.

4.2.1. Charge Reversal Time Concept

With respect to the relative size of the inductive reactance ,X_L ,the time taken by the charge reversal is non-instantaneous but is determined by the natural resonant frequency, $f = 1/2 \pi\sqrt{LC}$ of the TCSC circuit , following the fact that the TCSC conduction duration is nearly equal to half period which is equivalent to

$$f = T/2$$

$$= 1/2f$$

$$= {}^{1}/_{2} . {}^{1}/_{2}\ \pi\ \sqrt{LC}\ \ ; \quad f = 1/2\ \pi\sqrt{LC}$$

$$= {}^{1}/_{4}\ \pi\ \sqrt{LC}$$

Therefore , increasing the value of X_L in relation to X_C, the period for TCR conduction increases , and as a result , the zero crossing of capacitor voltage depends on the existing line current.

In addition, it is worth noting that the impedance of the TCSC does not offer an appreciable variation of the physical operational status of TCSC device [1,4] . This is on the condition that it must be comparatively smaller in relation to the size of the capacitor impedance so as to enable the series compensation control in accordance to the system demand.

5. Derivation of Equations For The Deformed TCSC Thyristor Current Wave Form, Deformed Capacitor Voltage Wave Form And Deformed Line Current Wave Form IN AC System

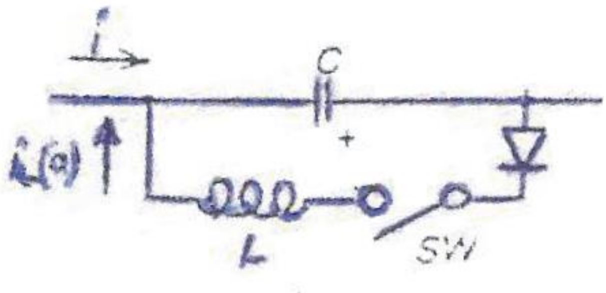


Fig. 8: Diagram showing the TCSC circuit with thyristor switch off

From the basic circuit above, the switch, SW is open and current is disallowed from flowing along the inductive branch ,thus the only current along the line is the source current , $i_{(t)}$ and the current from the capacitor. Applying Kirchoff's current law, we obtain

$$i(t) = ic(t) + i_L(\alpha) \qquad (3)$$

but iL(α) = 0 (open loop current as the thyristor switch is off)

then, i(t) = ic(t) + 0

Taking i(t) = I_0 Sinωt (ac source current of I_0 amplitude)

And $i_C(t) = {CdVc(t)}/{dt}$ (4)

By substitution,

I_0 Sinωt = ${Cdvc(t)}/{dt}$ (5)

Since the current in TCSC when the thyristor switch was off is the current through the capacitor (ie source current, I_0Sinωt)

Therefore, the voltage across the capacitor when the thyristor switch was of can be found as follows:

$I_0 \text{Sin}\omega t = {CdVc(t)}/{dt}$

Integrating both side of the equation,

$I_0 \int \text{Sin}\omega t \, dt = C \int dVc(t)$

I_0 / ω [Cosωt] = CV_C (t)

V_C (t) = I_0 /Cω [Cosωt]

But,1/Cω = X_C

V_C (t) = $I_0 X_C$ [Cosωt]

At closing of the switch /loop(thyristor fired on at angle,α):Closing the switch, SW at an angle ,α allows the flow of source current $i_{(t)}$ and $i_{L(t)}$,inductive current across the capacitor thus ,applying KCL, we obtain:

ic(t) = i(t) + i_L(α) (6)

Therefore,

${CdVc(t)}/{dt}$ = I_0Sinωt+ i_L(α) (7)

But at the instant of closing of the switch, t = 0 , the capacitor voltage ,Vc (t) is equal to the voltage V_L(t) built across the inductor.

Therefore,

V_C(t) = V_L(t) ,at t = 0 (as the switch closes)

But ,

$V_L(t) =$ Ldi/dt

Vc(t) = Ldi/dt (8)

From equation (7),

$I_0 Sin\omega t = i_L(\alpha) - [{}^{CdVc(t)}/_{dt}]$ (9)

SubstitutingV(t) in equ.(8) into equ.(9),

$I_0 Sin\omega t = i_L(\alpha) - [(Cd^2 i(t)) / d^2 t]$ (10)

Adopting Laplace transform for equ. (10),

$Sin\omega t = {}^{\omega}/_{(\omega^2 + S^2)}$ (11)

$i_L(\alpha) = -LCSi(\alpha)(0) - LC\, i_1(\alpha)(0)$

$[(Cd^2 i(t)) / d^2 t] = I_L(\alpha)(s) + I_L(\alpha)(s)LCS^2$

$= I_L(\alpha)(s)[1 + LCS^2]$ (12)

By substitution,

$I_0[{}^{\omega}/_{(\omega^2 + S^2)}] = I_L(\alpha)(s) + I_L(\alpha)(s)LCS^2 - LCS\, i(\alpha)(0) - LC\, i_1(\alpha)(0)$

Taking $i_L(\alpha)(0)$ as the thyristor current at t = 0 (initial current value) , just before the thyristor/ switch is fired /closed ,and $i_1(\alpha)(0)$ as the initial current derivative and all equal to zero , we will have

$I_0[{}^{\omega}/_{(\omega^2 + S^2)}] = I_L(\alpha)(s) + I_L(\alpha)(s)LCS^2$

$= I_L(\alpha)(s)[1 + LCS^2]$

$I_L(\alpha)(s) = I_0[{}^{\omega}/_{(\omega^2 + S^2)}][1 + LCS^2]^{-1}$

But, $[1 + LCS^2]^{-1} = [{}^{1}/_{(1 + LCS^2)}]$

Dividing the numerator and denominator by *LC*, we have

$[1 + LCS^2]^{-1} = 1/LC[{}^{1}/_{(1/LC + S^2)}]$

$\omega_0 = {}^{1}/_{\sqrt{LC}}$

$\omega^2_0 = {}^{1}/_{LC}$

Therefore, $I_L(\alpha)(s) = I_0[\omega^2/(\omega^2+S^2)]\,[\omega_0^2/(\omega_0^2+S^2)]$

Put in inverse Laplace form, we have

$I_L(\alpha)(s) = I_0[\omega^2/(\omega^2+S^2)\cdot \text{Sin}\,\omega t - \omega_0^2/(\omega_0^2+S^2)\cdot \frac{\omega}{\omega_0}\text{Sin}\omega_0 t]$

Let B = $\omega_0^2/(\omega_0^2+S^2)$

By substitution,

$I_L(\alpha)(s) = I_0[\,B\text{Sin}\,\omega t - B\frac{\omega}{\omega_0}\text{Sin}\omega_0 t]$

$I_L(\alpha)(s) = I_0 B\,[\text{Sin}\,\omega t - \frac{\omega}{\omega_0}\text{Sin}\omega_0 t]$

5.1.1Analysis Of The Derived Equations:

From the derived equations above, the source current ;thyristor current ,capacitor current and voltage of the TCSC can be analyzed with reference to ωt range just as shown below:

Recall that:

Source current = I_0 Sin ωt

Voltage across the capacitor when the inductor branch was open

= $I_0\,X_C\text{Cos}\,\omega t$

Voltage across the capacitor when the thyristor is fired at α angle

= $I_0\,X_C\text{Cos}\alpha$

The current along the inductor branch at the closing of switch/thyristor

$I_L(\alpha)(s) = I_0 B\,[\text{Sin}\,\omega t - \frac{\omega}{\omega_0}\text{Sin}\omega_0 t]$

Then,

Table 1.0 At $0 \le \omega t < \alpha$:

Capacitor current	*Thyristor current*	*Capacitor Voltage*
I_0 Sin ωt	0	$I_0\,X_C\text{Cos}\,\omega t$

At $\alpha \leq \omega t < \pi$:

Capacitor current	*Thyristor current*	*Capacitor Voltage*
$I_0 \text{Sin}\omega t + {}_0B[\text{Sin}\omega t - \frac{\omega}{\omega_0}\text{Sin}\omega_0]$	$IoB[\text{Sin}\pi - \frac{\omega}{\omega_0}\text{Sin}\pi\omega]$	$-I_OB[X_L\cos\pi - X_L\cos\pi\omega - I_OX_C\cos\alpha]$

At $\pi \leq \omega t < (\pi+\alpha)$:

Capacitor current	*Thyristor current*	*Capacitor Voltage*
$I_0 \text{Sin}\omega t$	0	$I_0X_L\text{Cos}(\pi + \alpha) + BI_0[X_L \text{Cos}\pi - X_L \text{Cos}\omega\pi] - I_0X_C \text{Cos}\,\alpha$

At $(\pi+\alpha) \leq \omega t < 2\pi$:

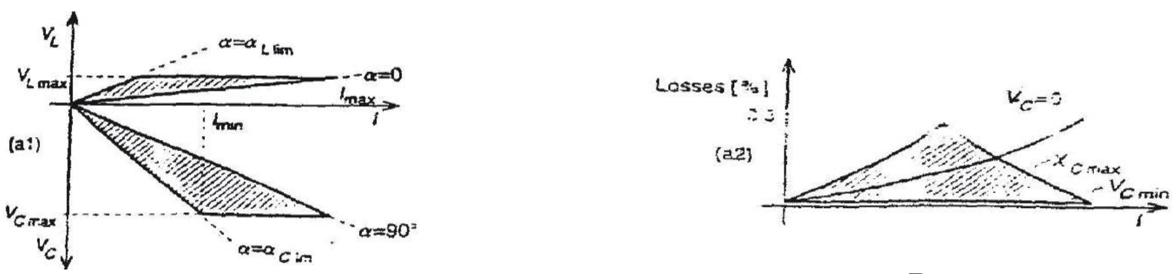
Capacitor current	*Thyristor current*	*Capacitor Voltage*
$I_0 \text{Sin}\omega t - I_0B[\text{Sin}\omega t - \frac{\omega}{\omega_0}\text{Sin}\omega_0 t]$	$-I_0B[\text{Sin}(\pi+\alpha) - \frac{\omega}{\omega_0}\text{Sin}(\pi+\alpha)]$	$I_O B[X_L\text{Cos}(2\pi) - I_0 X_L\text{Cos}2\pi\omega] - I_0 X_C\text{Cos}(\pi+\omega) + BI_0X_C \text{Cos}\pi - X_L \text{Cos}(\pi\omega)] - I_0X_C \text{Cos}\alpha$

Skeletal tabular format showing the derived TCSC deformed voltage and current wave equation, with thyristor firing angle as relates to the system angular frequency

6. TCSC Compensating Voltage / Line Current Characteristics

6.1. Voltage Compensating Mode

A graph of compensating voltage versus the system line current is shown below, figure 9. It reveals the functional characteristics of the basic thyristor controlled series compensator with respect to the operational range of the firing angles.



A

B

Fig 9 Diagram showing (***a) Compensating voltage-current (b) Losses versus current characteristics***

Within the capacitive region,the minimum delay angle, α_{CLim} fixes a maximum compensating voltage limit up to the existing minimum line current, I_{Min}. As a result, the maximum rated capacitive voltage, V_{cmax} restrains the system operation until the rated maximum current is attained [1,4]. In inductive region; however, the voltage is obviously limited at low magnitude of line current and maximum rated thyristor current[5,4] . A graph of the corresponding losses (in percentage of the rated output)that is plotted against the system line current for voltage compensating mode (in the operating capacitive region)is as shown in figure 9 b ;considering the maximum and minimum compensating voltages as well as the by pass operational mode.

These losses are virtually due to thyristor controlled reactor(TCR) of the TCSC; and they include losses due to thyristor conduction and switching as well as that due to ohmic loss (I^2R) of the inductor element[4]. The loss/current characteristic has a direct relationship with the voltage compensation characteristics given in figure 9 a above. As seen, the losses and line current increase in the same proportion with the maximum fixed conduction angle of TCR and the minimum-delay angle, α_{CLim}. Then decrease in the same manner as the firing angle,α increases within the range ,($\alpha_{clim} < \alpha < \pi/2$) in order to create a fixed capacitor voltage that is quite below the minimum voltage constraint.

6.2. Impedance compensating mode

The essence of application of TCSC is to build a maximum rated compensating reactance for the system line current. As a result, choice of TCSC and its associated TCR segment is made such that the maximum capacitive reactance should be maintained at the maximum value of α_{clim}. See the illustration on the graph below:

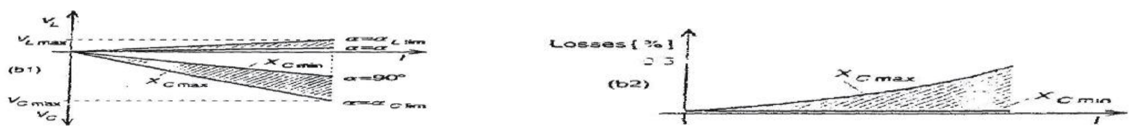


Fig.10 Diagram showing the graph of (a) Compensating impedances versus current and (b) Losses versus current

With TCSC, the minimum attainable capacitive compensating impedance is the impedance of the capacitor itself which is theoretically obtained when thyristor firing angel equals 90^0 (i.e. $\alpha = 90^0$) [5].This is the angle at which the thyristor valve is assumed non-conductive. The thyristor controlled series capacitor is usually designed to have transient voltage and current rating that are confined within a specified time duration [4]. It is very good to note that the maximum voltage and current limits are very essential and are purposely designed, keeping the thyristor valve, the inductor element and capacitor component within a system tolerable rated value so as to meet a specific network desired application.

The diagram above, figure 10, shows the attainable compensating reactance versus line current functional characteristics of the compensator that commensurate with the voltage compensation mode. This indicates that TCSC have no capability of capacitive impedance control below the minimum value, X_{cmin} (the system frequency impedance of the capacitor) and up to X_{Lmin} which is the system frequency impedance of the reactor [1, 5]. The uncontrolled capacitive margin can be substantially large if the composition of the TCSC is a single unit confinement. However, the difficulties that attend the large control band is usually the inability of achieving system dynamic stability control for effective power oscillation

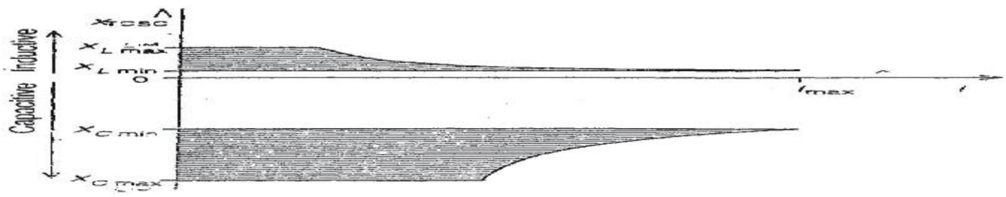


Fig.11 Diagram showing a graph of Capacitive and Inductive reactances versus line current

damping using TCSC circuit. Therefore, splitting the installation of TCSC into many modular units can necessitate the sequential placement of the modules in the line; and in effect, narrowing down the uncontrolled band to a very minute size.

6.3. Harmonics

In determination of the maximum voltage and current ratings of a TCSC for satisfaction of a given system operating conditions, the effects of harmonics should be heavily considered ;more especially, in the face of worst case system operating condition[8]. Outside this defined operating condition, the TCSC should be shielded against system over voltage and current surges using a shunt connected external protective devices such as

1. MOV arrester
2. Triggered spark gap
3. Bypass breaker or
4. TCR itself with a back up breaker (in bypass mode)

6.4. Effect of the TCR Reactor and the Fixed Capacitor Impedance in TCSC Design

The major operation of the TCSC circuit for reactive power compensation is determined by the proportion of X_L and X_C constituents of the compensator[1]. In effect, the feasibility of power system reactive power concept for basic action of the TCSC are confined in the two impedance properties of the compensator[1] .In real practice, the factor for effective function of the device is chosen to be the inductance-capacitance ratio of 0.133 (i.e. $^{XL}/_{XC}$ = 0.133), necessitating the natural resonant frequency value of 2.74 times the $60H_Z$ fundamental frequency of the TCSC compensator. Practically, the ration of X_L to X_C can be obtained within the range of 0.1 to 0.3 based on the system application requirement; and network prevailing constraints. Thus, the TCR inductor element property does not alter the natural behaviour and physical operation of the TCSC circuit, as long as it is significantly small in comparison with the impedance of the capacitor to give room for efficient system series compensation [4].

6.4.1. Merit of small size of X_L element in TCR series reactor

1. The small size of X_L (inductive element in TCR branch) is essential in providing a well-defined charge reversal and control of period of time for compensating voltage.

2. The smallness in size of X_L could be appreciated owing to its facilitation of adequate protective bypass against high current surge experienced during system fault.

6.4.2. Demerit of small size of X_L element in TCR series reactor

1. The presence of TCR branch of the TCSC necessitates the flow of harmonic current within the circuit. This circulates through the fixed capacitor to generate harmonic voltages [4,1]. And so the magnitude of this harmonic qualities especially the current tends to magnify as large amount of current flows through the TCR due to the small size and value of the reactor element. This in effect gives rise to high magnitude of harmonic voltages within the circuit.
2. The smallness of X_L also decreases the range of the thyristor delay angle control and as a result, the close loop parameter regulations becomes very difficult for effective implementation of system compensation
3. It enables large short-duration current pulse in thyristor valve ,thereby increasing the TCR current rating and possibly the voltage rating too

6.5. Disadvantage Of A TCR Segment Of TCSC In Power System

It should equally be noted that the presence of harmonics in the power system as generated by TCR in a TCSC compensator do largely cause the deformation of natural sinusoidal wave form of electric power system quantities(eg. Ac current & voltage wave form)

7. Conclusion

The possible challenges of the past in Electricity industries are today profitably managed with adequate solutions which are purely based on high power automation as regards the soaring extent of dynamic response often associated with the FACTS equipment. With the incorporation of the TCR branch in the equipment, as we already discussed , the fast switching response of the device is exceedingly upgraded, and of course, quite much more upgraded compared to the usual power system static Var compensators like ordinary capacitor banks , reactor etc. As a result, the Flexible Alternating Current Transmission System (FACTS) Equipment is today enabling the load ability cases in power system to actually earn a maximum ease with effect to initiating suitable level of load that can run along the lines within the designed thermal capacity of the system. As such, the real time operational concept of this equipment is becoming issues of major concern; looking at the behavioral time management of the TCR branch whose X_L element is a determinant factor for sole purpose of setting a well-defined charge reversal and control period of time for voltage compensation. And by this, the operation of the device can offer a considerable amount of relief in system line parameter control, even as the equivalent parameters of power network such as the overall line reactance etc can now be easily adjusted using some essential components of the device in order to regulate the amount of power quantities to a certain system required level that could match the system capacity with no room for initiating any natural condition that may not be adequately handled at any time and any where within the system environment. In effect, the device is accepting a better position in field application more than many other static Var compensators, and this is as a result of their lofty dynamic response in arising to such challenges as sudden high voltage rise due to instantaneous load relief and unexpected system voltage fall due to large amount of load switching into the system. As such, such long – time used reactive power compensation equipments like capacitors, reactors etc will soon be faced-out when the emergence of these active, quick, self system controlling and compensation equipment are fully situated in our daily system operation .And this will effectively increase efficiency and operational reliability in power system management; especially, among the technologically growing countries of the world.

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