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Fixed Capacitor Thyristor -Controlled Reactor (TCR) Static Var Compensator (SVC)

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ABSTRACT *- Since the load varies from time to time, the reactive power balance in a grid varies as well. This results in unacceptable voltage amplitude variations, which may lead to voltage depression, or even voltage collapse. In an electric utility network, it is desirable to regulate the voltage within a narrow range of its nominal value (±5% range around their nominal values). Voltage drop on transmission and distribution systems is largely determined by reactive power. To control dynamic voltage swings under various system conditions and thereby improve the power system transmission and distribution performance, a fast acting Static VAr Compensator (SVC)is required to produce or absorb reactive power so as to provide the necessary reactive power balance for the system. In this paper an SVC configuration known as fixed capacitor, thyristor-controlled reactor is examined. The paper is intended to show how this SVC works in a network to improve system efficiency. The control equations are derived. These equations are used to demonstrate the effectiveness of the SVC in controlling the reactive power which flows in the system and consequently regulatethe system voltage,and raise the operating power factor to near-unity.*

KEYWORDS *- Reactive Power, static varcompensator (SVC), voltage drop, thyristor-controlled reactor, Power Factor, firing angle, and capacitor.*

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I. INTRODUCTION

The development of power electronics technology has led to the extensive use of SVCs to dynamically support the voltage in power systems, and also for stability control (Su and Chen, 2004).Thus, Application of SVCs in Power systems results in reduction of losses in the system by improving the power factor, improvement of transient stability, enhancement ofactive power transfer capability, and alleviation of load imbalance in individual phases (Chano et al., 1995), (Chen et al., 1999). Any modest reduction in transmission losses by limiting the flow of load reactive current along the transmission lines means considerable cost savings in both power capacity and energy production (Hammad, 1996). Traditionally, fixed shunt capacitors, mechanically switched capacitors, synchronous condensers, and saturated reactors were employed as SVCs to control the system voltage. The thyristor-controlled reactor (TCR)is a var controller, which by means of a power electronic interface can provide a quick control over the static reactive power, (Ekanayake, 1996), (Benghanem and Draou, 2006), (Trujillo et al., 2013). This TCR provides dynamic var compensation and a power factor very close to unity. Dynamic compensation uses combinations of variable inductive and capacitive elements with solid-state devices, such as thyristors, gate turn-off thyristors (GTO), and insulated-gate bipolar transistors (IGBT) for switching to achieve faster response to changes in system conditions. Characteristically, they are able to rapidly and smoothly vary the reactive power output by controlling the firing delay angles of the solid-state switches, to compensate for changing system conditions. They use a sensing and control system to decide how much reactive power must be applied to or drawn from the system to achieve the required level of compensation (Lockley and Philpoitt, 2000).There must be a control system that determines the gating instants and issues the gating pulses to the solid-state switches in response to some system changes. The control system processes various measured parameters of the compensated system like bus voltage, system frequency e.t.c. and produce a control characteristic as shown in Fig. 1 (Stephen, 1989). Fig. 1 represents the SVC response to system voltage fluctuation, where three of an infinite number of system load lines are shown. The function of the SVC is to maintain the voltage of the bus connected at a constant value (Liu andGao, 2001). V is the ac system voltage. One of the load lines represents a system condition in which the system voltage coincides with compensator set-point voltage V_O, taken to be 1.0 pu. In this case, the SVC output is zero. The second system load line intersects the compensator characteristics at a point which corresponds to a system condition where the system voltage has increased to V_1 (1.1p.u.), thus actuating the SVC to produce a lagging current, I_1 to reduce the voltage to the set-point value. If the voltage drops to a value, V_2 (0.9 p.u.) below the set-point, as indicated by the third load line, the SVC produces a leading current, I_2 to restore the terminal voltage to normal value. Thus, the values 0.9 and 1.1 are simply examples of values of the ac system voltage at which the compensator may be actuated. Fig. 2 shows the connection of the SVC to the ac system.

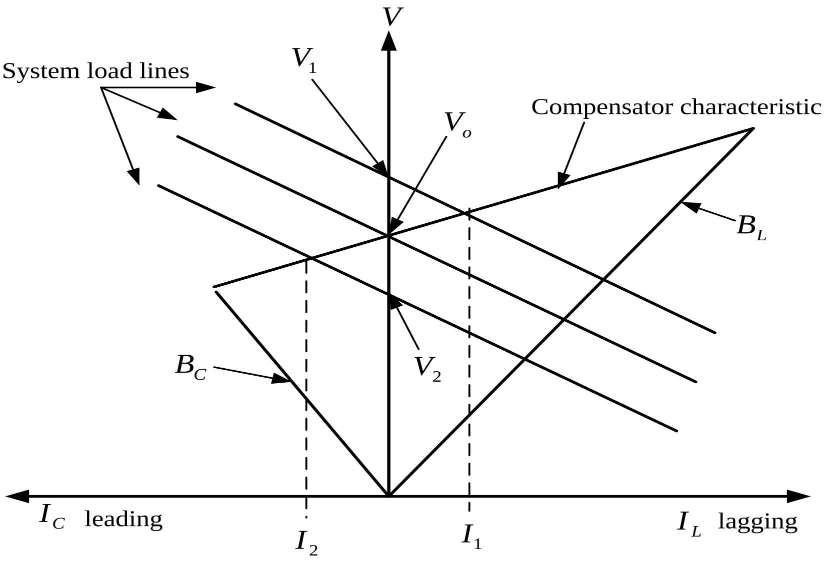

Fig. 1 Dynamic operating characteristics of SVC

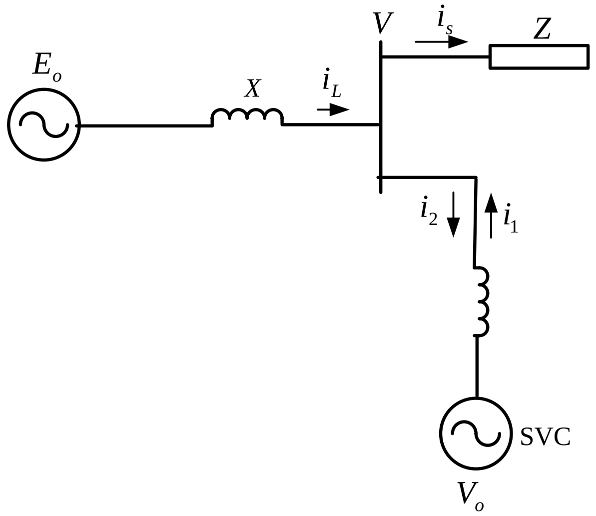

Fig. 2. Connection of SVC to ac system

This paper investigates how the TCR is used to control the flow of reactive power, and so implement power factor correction. Harmonics generation by the TCR is also examined.

II. METHODOLOGY

Fig. 3 is the TCR configuration.

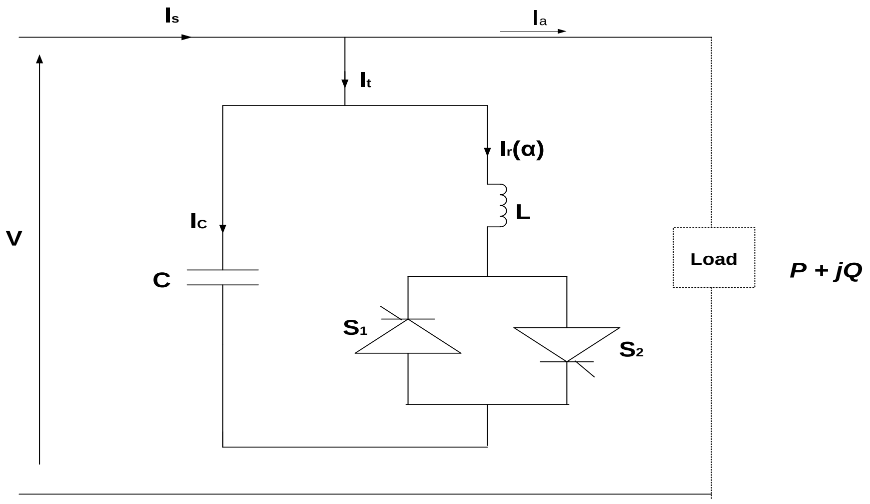

Fig. 3 Fixed Capacitor Thyristor-Controlled Reactor (FC-TCR)

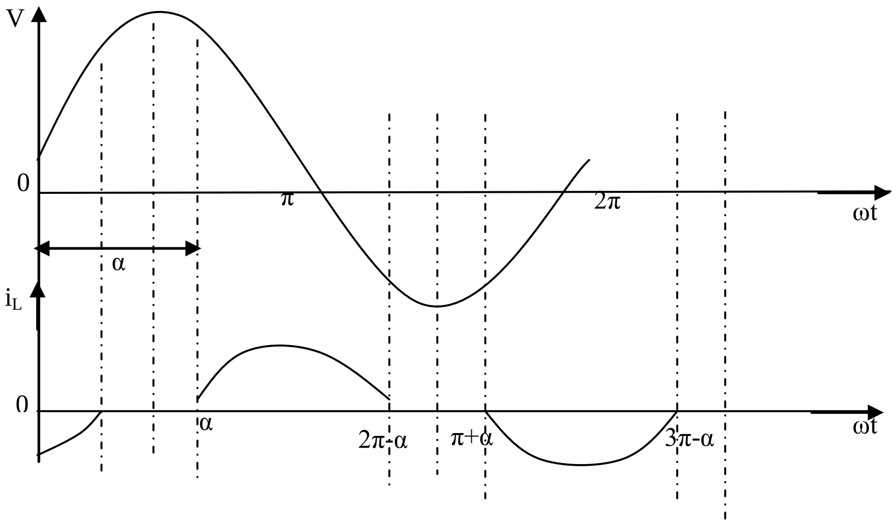

Fig.4 Inductor Current waveform

In this SVC an inductor (reactor) is in series with a bank of thyristors connected in anti-parallel (Zhiet al., 2006). This arrangement is placed in parallel with one or more constantly energized capacitor banks as shown in Fig. 3a. This is also known as fixed capacitor, thyristor-controlled reactor compensator (FC-TCR). The capacitor supply a constant quantity of vars to the system and the reactor supplies variable lagging current, to counteract the capacitive current, to an extent controlled by the firing angle of the high-power thyristors. By varying the firing angle between 90 and 180^o the magnitude of fundamental component of current and apparent inductance of the reactor can be continuously adjusted. This SVC can give a maximum of vars contribution of the combined ratings of the capacitor and inductor, and a minimum of the capacitor rating minus the reactor rating. Since the reactor current is adjusted by phase-angle control of the thyristors, harmonic currents are generated. Filters are added to suppress these harmonics. In this scheme, the inductor current is controlled by the delay angle, α in each half cycle, with respect to the peak of the applied voltage. The inductor current in Fig. 4 can be found as follows.

For the positive half-cycle:

$$L\frac{di_L}{dt} = V\sin\omega t \tag{1}$$

$$\int di_L = \frac{V}{L}\int \sin\omega t dt$$

The solution of equation (1) is a general solution given as:

$$i_I = -\frac{V}{\omega L}\cos\omega t + A \tag{2}$$

Where A is the constant of integration.

At $\omega t=\alpha$, $i_I=0$, and $A=\frac{V}{\omega L}\cos\alpha$

So,

$$i_I=\frac{V}{\omega L}(\cos\alpha-\cos\omega t)\,(3)$$

Similarly, it can be shown that, for the negative half-cycle:

$$i_I=\frac{V}{\omega L}(\cos\alpha+\cos\omega t)\,(4)$$

By Fourier analysis, the inductor (reactor) current is:

$$i_I=\frac{1}{2}a_o+\sum_{n=1}^{\infty}(a_n\cos n\omega t+b_n\sin n\omega t)\,(5)$$

And the fundamental of the inductor current is:

$$i_{L1}=\frac{1}{2}a_o+a_1\cos\omega t+b_1\sin\omega t\,(6)\;a_o=\frac{1}{2\pi}\int_o^{2\pi}i_L\,d\,\omega t\,(7)$$

$$a_n=\frac{1}{\pi}\int_0^{2\pi}i_L\cos n\omega t\,d\,\omega t\qquad(8)$$

$$b_n=\frac{1}{\pi}\int_0^{2\pi}i_L\sin n\omega t\,d\,\omega t\quad(9)$$

From Fig. 3b,

$$a_o=\frac{V}{2\pi\omega L}\left\{\int_{\alpha}^{2\pi-\alpha}(\cos\alpha-\cos\omega t)\,d\,\omega t-\int_{\pi+\alpha}^{3\pi-\alpha}(\cos\alpha+\cos\omega t)\,d\,\omega t\right\}(10)$$

$$a_o=0$$

$$a_n=\frac{V}{2\pi\omega L}\left\{\int_{\alpha}^{2\pi-\alpha}(\cos\alpha-\cos\omega t)\cos n\omega t\,d\,\omega t-\int_{\pi+\alpha}^{3\pi-\alpha}(\cos\alpha+\cos\omega t)\cos n\omega t\,d\,\omega t\right\}\,(11)$$

$$a_1=\frac{V}{\pi\omega L}\left\{\int_{\alpha}^{2\pi-\alpha}(\cos\alpha-\cos\omega t)\cos\omega t d\omega t-\int_{\pi+\alpha}^{3\pi-\alpha}(\cos\alpha+\cos\omega t)\cos\omega t d\omega t\right\}(12)$$

$$a_1=-\frac{V}{\pi\omega L}[2\pi-2\alpha+\sin 2\alpha](13)$$

$$b_n=\frac{V}{2\pi\omega L}\left\{\int_{\alpha}^{2\pi-\alpha}(\cos\alpha-\cos\omega t)\sin n\omega t\,d\,\omega t-\int_{\pi+\alpha}^{3\pi-\alpha}(\cos\alpha+\cos\omega t)\sin n\omega t\,d\,\omega t\right\}(14)$$

$$b_1=\frac{V}{\pi\omega L}\left\{\int_{\alpha}^{2\pi-\alpha}(\cos\alpha-\cos\omega t)\sin\omega t d\omega t-\int_{\pi+\alpha}^{3\pi-\alpha}(\cos\alpha+\cos\omega t)\sin\omega t d\omega t\right\}(15)$$

$$b_1=0\,(16)$$

Thus, a_o= 0 ;b_1= 0; and $a_1=-\frac{V}{\pi\omega L}[2\pi-2\alpha+\sin 2\alpha]$

The fundamental of the inductor current is:

$$I_{l1}(\alpha)=-\frac{V}{\pi\omega L}[2\pi-2\alpha+\sin 2\alpha]\cos\omega t\,(17)$$

$$\frac{\pi}{2}\le\alpha\le\pi$$

The amplitude of the fundamental of the inductor current is:

$$I_{LF}(\alpha) = -\frac{V}{\pi \omega L}[2\pi - 2\alpha + \sin 2\alpha]$$

(18)The capacitor current is:

$$I_C \quad = \quad \omega C V$$

(19)

Where C = capacitance

The compensating current is:

$$I_{Com} = I_C + I_{LF}(\alpha)$$

$$I_{Com} \quad = V\left[\omega C - \frac{1}{\pi \omega L}(2\pi - 2\alpha + \sin 2\alpha)\right] \quad (20)$$

The compensating current I_{Com} and hence, the effective impedance of the compensator can be varied by adjusting thyristor delay angle α. I_{Com} is positive when the total current is capacitive and negative when the total current is inductive**.** As a result of phase angle α, this device generates harmonics. For identical positive and negative current half cycles only odd harmonics are generated. The maximum amplitudes of the 3rd, 5th, 7th, 9th, 11th, and 13th are 13.8, 5.0, 2.5, 1.6, 1.0 and 0.7 per cent respectively of the maximum inductor current obtained with full condition (α=0). The delay angle at which the firing of the thyristor switch is to be initiated is the final information required from the control. Fig. 5 and Fig.6 show the waveforms of theTCR current.Fig. 5 shows the basic inductor current, where i_{I1} is the fundamental component. The inductor (reactor) current is not a pure sine wave at α > 90°. i_I consists of odd harmonics, h of the order 3, 5, 7, 9, 11, 13, … whose amplitudes as a ratio of I_{I1} depend on α.

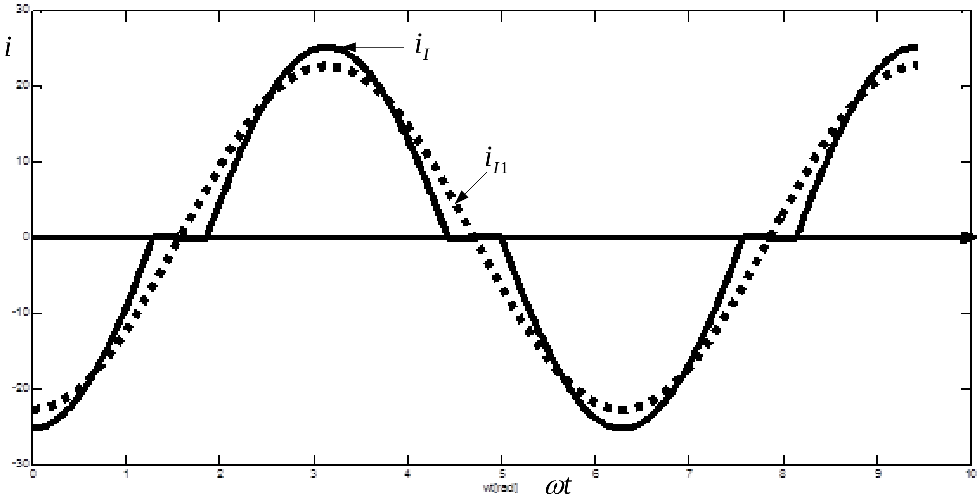

Fig. 5 The output current of the TCR

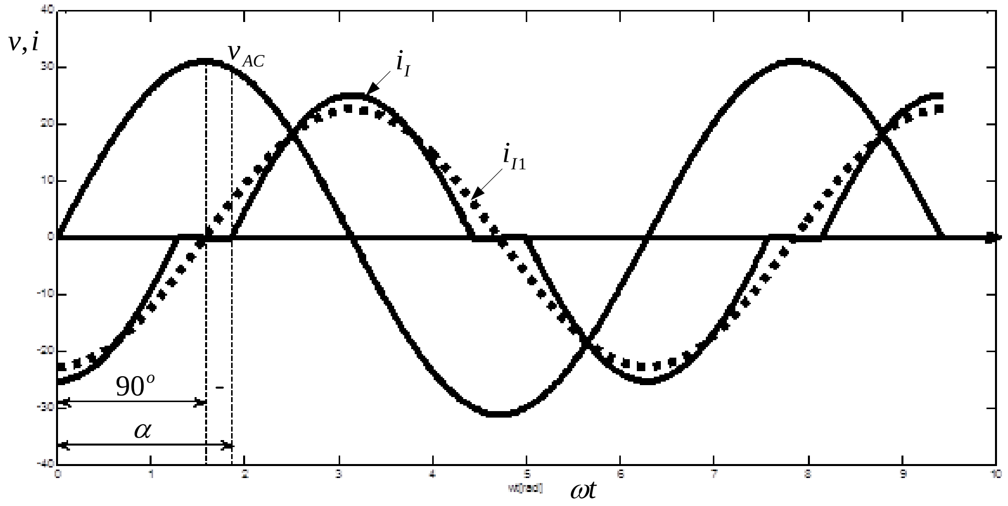

Fig. 6output current of a TCR with system voltage.

v_{AC} = System voltage

i_I = Inductor current

i_{I1} = fundamental component of inductor current

Fig. 5 and Fig. 6 show that, as α is increased, i_{I1} (the fundamental component of the inductor current) decreases, thus allowing a control over the effective value of inductance, L_{eff} connected to the utility voltage.

III. RESULTS AND DISCUSSION

Referring to Fig. 3, with load of impedance $Z = (12 + j12.6)\ \Omega$ connected, the system was operating at 0.69 power factor lagging. Fig. 7shows the application of the TCR to compensate for reactive power, and consequentlyraise the power factor of the system. The TCR parameters are given as L = 20mH, C = 400μF, and V = 220V. It can be observed from the Fig. 7 that the power factor has been raised from 0.69 lagging to 0.9 lagging when α was 106^o, while Fig. 8 indicates power factor of 0.996 lagging with α equal to 111^o. At this angle, the harmonic amplitudes as a percentage of $I_{I1}$are shown in table 1. Fig. 9 is bar chart representing the current harmonics. It is a common practice to connect three-phase TCR in delta (Δ), so that the third-order and multiples of the third-order harmonics can circulate through the inductors and do not enter the ac system (Gyugyi and Tailor, 1980). The capacitor, in parallel with the inductor, apart from supplying the system var requirements, filtered out high-frequency harmonics, while the fifth and seventh harmonics could be filtered out by series-tuned filters.

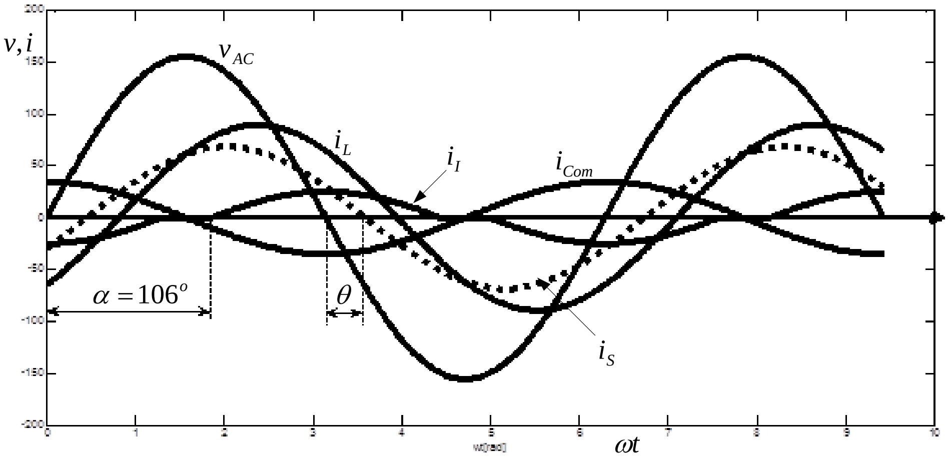

Fig. 7the associated waveforms of the TCR – power factor raised from 0.7 lagging to 0.9 lagging (α = 106°)

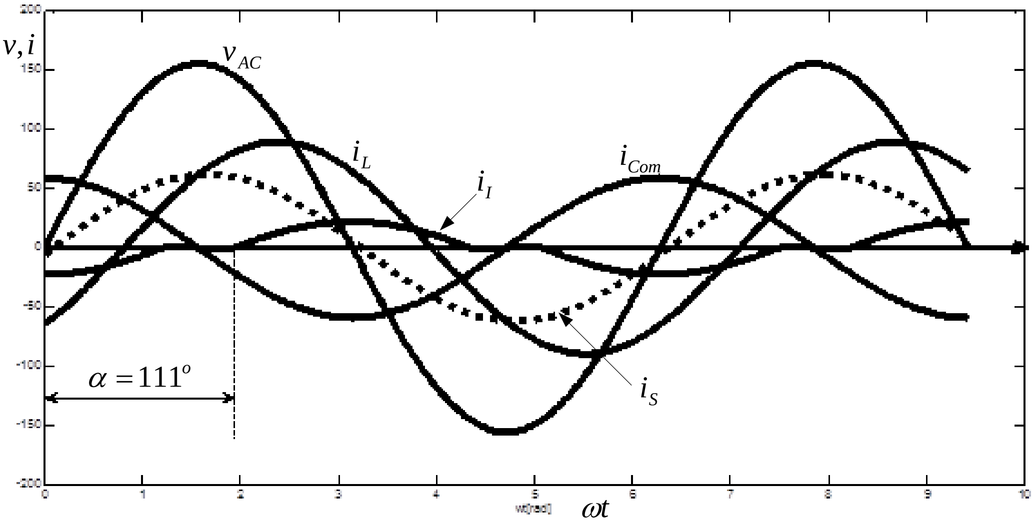

Fig. 8 the associated waveforms of the TCR – power factor raised from 0.7 lagging to unity (0.996)
(α = 111°)

v_{AC} = AC system voltage

i_I = Inductor current

i_L = Load current

i_{Com} = Compensator current

$i_S = i_L + i_{Com}$

θ is the angle between the system voltage, v_{AC} and the compensated current, i_S .

Table 1 Percentage values of harmonic currents

Harmonic order	3	5	7	9	11	13	15	17	19	21	23	THD (%)

$\frac{h_n}{h_1}\%$	22.5	8.83	2.6	0.35	1.38	1.28	0.68	0.032	0.38	0.5	0.34	24.4

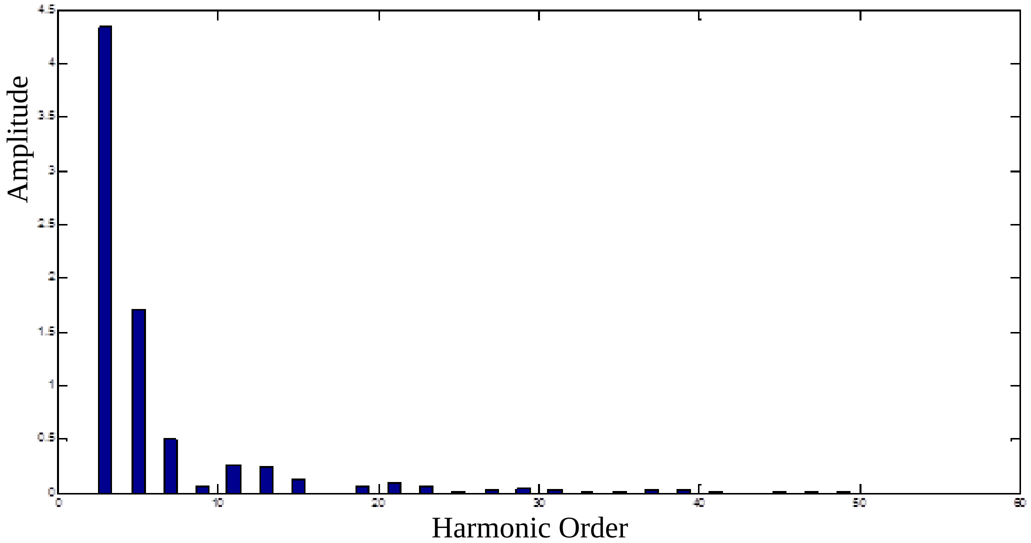

Fig. 9 bar chart of current harmonics

I_{I1} = 19.3A

$$L_{eff} = \frac{V}{\omega I_{I1}} = \frac{220}{(2\pi f)x19.3} = 36.3mH$$

And the lagging reactive power drawn by the inductor (or reactor) at the fundamental frequency was:

$$Q_1 = V_1 I_{I1} = \frac{V_1^{\ 2}}{\omega L_{eff}} = 4248.5\text{VAr}$$

Capacitor current, I_C = 27.6A

Reactive power generated by capacitor:

$$Q_C = -\omega CV^2 = -2\pi f CV^2 = -6082\text{VAr}$$

$$Q_{Com} = Q_I + Q_C$$

$$Q_S = Q_L + Q_{Com}$$

Fig. 10shows the various reactive powers associated with the TCR

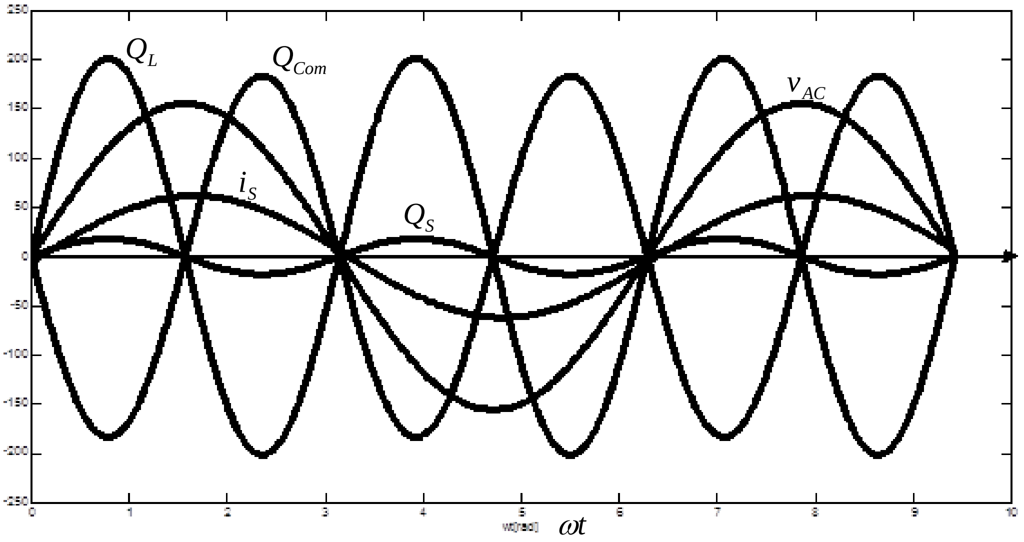

Fig. 10 reactive powers of the ac system and TCR for α = 111^{o}

v_{AC} = AC system voltage
Q_L = Load reactive power
Q_{Com} = Reactive power generated by TCR
Q_S = Reactive power from source
i_s= Source current

The system operating voltage was 220V. The load power factor is 0.7. Thus the current and the power drawn from the source by the load are 12.644A and 2782VA respectively. In other words the reactive components of current and power are 9.16A and 2014VAr respectively. The control system senses this conditions within the system and then actuates the TCR – the thyristors are fired at an angle α = 111^{o} of the voltage waveform. Reactive component of power/current is then injected into the system, near the load, by the TCR in order to achieve the desired power factor.As stated earlier, by varying the firing angle, α between 90 and 180^{o} the magnitude of fundamental component of the current and apparent inductance of the reactor, *L*can be continuously adjusted - equation (17). Thus *L* is a function of α, and so $L_{eff} = 36.3$ mH is the value of inductance at which the power factor becomes 0.996. This value of power factor may be obtained as follows:

Load current, $I_L = \frac{V}{Z} = \frac{220}{17.4} = 12.644A$

Apparent power supplied by the ac system, $S = V x I_L = 220 x 12.644 = 2782$ VA

Vars supplied by the ac system, $Q_L = 2782 x \sin 46.4^{o} = 2014$ VAr

Real power supplied by the ac system, $P_{AC} = 2782 x \cos 46.4^{o} = 1918$ W

Vars generated by capacitor, $Q_C = -6082$ VAr

Vars drawn by inductor, $Q_I = 4248.5$ VAr

Vars generated by TCR, (Vars injected into the ac system) $Q_{Com} = -6082 + 4248.5 = -1833.5$ VAr

Resultant Vars supplied by the ac system, $Q_S = -1834 + 2014 = 180$ VAr

Power factor $= \cos\left[\tan^{-1}\left(\frac{180}{1918}\right)\right] = 0.996$

Thus, the range of minimum and maximum vars the TCR can add or take from the system is 0 and1834VAr. Fig. 6b and Fig. 7, show that $v_{AC}$and$i_S$arein phase (power factor = 0.996) after 1834VAr have been injectedinto the system. Similarly, it can be shown that the vars that can be injected into the system by the TCR in order to achieve 0.9 power factor is 1085VAr – Fig 6a. The amount of vars supplied by the TCR depends on the system conditions and the desired power factor.

IV. CONCLUSION

In this paper, the principle of operation of the TCR compensator has been investigated. The governing equations have been derived, and then used to show how a system with low power factor could be improved. A near-unity power factor was achieved by the use of the TCR compensator. The harmonics content of the TCR current has been shown in table 1 – the total harmonic distortion (THD) was calculated to be 24.4%. However, this var compensator suffers from the disadvantages of bulkiness, high harmonic distortion, and relatively slow response to system conditions. These shortcomings can be overcome by the application of switch-mode dc-to-ac converter, otherwise known as voltage source inverter (VSI). Thyristors can also be replaced by faster switches like IGBTs, (GTOs).

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