# Binary Current Generation with Transient Free Switching for TBSC Compensator

Swapnil Patil, Nikhil Kumbhar, A.M.Mulla and D.R.Patil, *Member, IAENG*

***Abstract*— The advanced shunt compensators are most widely used for reactive power compensation and harmonics mitigation, which is neither cost effective nor completely harmonic free. TBSC bank compensators are free from harmonics and provide a perfectly sinusoidal reactive compensating current in binary sequential form. The transient free switching of these thyristors takes place with the proper instant of switching time along with voltage across the capacitors. These aspects are dealt with in this paper. Simulation results are shown for transient free switching and binary current generation.**

***Index Terms*—TBSC, transient free switching, binary current generation, switching strategies and thyristor**

## I. Introduction

IT is well documented in literature and through public discussions at various levels that a substantial power loss is taking place in our low voltage distribution systems on account of poor power factor, due to inadequate reactive power compensation facilities and their improper control. Switched LT capacitors can directly supply the reactive power of loads and improve the operating condition. Government of India has been insisting on shunt capacitor installations in massive way and encouraging the state electricity boards through Rural Electrification Corporation and various other financing bodies[1, 2, 3].

The expansion of rural power distribution systems with new connections and catering to agricultural sector in wide spread remote areas, giving rise to more inductive loads resulting in very low power factors. The voltages at the remote ends are low and the farmer‘s use high HP motors operating at low load levels with low efficiencies. This is giving rise to large losses in the distribution network. Thus there exists a great necessity to closely match reactive power with the load so as to improve power factor, boost the voltage and reduce the losses. The conventional methods of reactive power supply are through switched LT capacitors, mostly in equal steps in various automatic power factor controllers developed by number of companies[4, 5].

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In this paper, a more reliable, technically sound, fast acting and low cost scheme is presented by arranging the thyristor switched capacitor units in five binary sequential steps. This enables the reactive power variation with the least possible resolution.

As there is reduction in loss with shunt compensation in the feeders, the efficiency increases and conservation of energy takes place. Besides the enhancement of transformer loading capability the shunt capacitor also improves the feeder performance, reduces voltage drop in the feeder and transformer, better voltage at load end, improves power factor and improves system security, increases over all efficiency, saves energy due to reduced system losses, avoids low power factor penalty, and reduces maximum demand charges[6, 7].

A capacitor subjected to switching operations is invariably associated with the transient phenomenon. The voltage across a capacitor cannot be changed abruptly and when switched on at t = 0+ it acts like a short circuit. In their application as a shunt compensator, they are provided with current limiting reactors. However, in LT applications the problem is not that severe. A shunt capacitor connected across a load injects reactive power and directly compensates the load reactive power. Shunt capacitors are widely employed in both LT and HT systems, on account of their attractive features. Numbers of advances have taken place in the design and manufacture of both LT and HT capacitors. Once they are installed in a system, they are long lasting, give trouble free service and highly reliable if they are provided with requisite protection [8, 9].

## II The Proposed Capacitor Bank Switching:

A capacitor bank when energized or d-energized by switching on or off, it is subjected to both voltage and current transients. In order to understand this phenomenon consider the electrical circuit energizing an isolated capacitor bank as shown in fig.1.

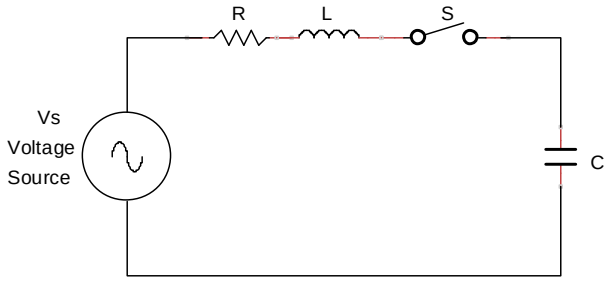


Fig.1 Energizing of capacitor through switch

In fig.1 shows electrical equivalent circuit for energizing an isolated capacitor bank from a predominantly inductive source. Immediately following the closure of switch, a high frequency and large magnitude current flows into the capacitor, so as to equalize capacitor voltage with the

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system voltage. The voltage surge and the inrush current depend on the instant at which the switch is closed on the supply wave form. The voltage surge for an isolated grounded star bank can reach a maximum of 1.8/2.0 per unit as shown in fig.2.

Fig.2 gives the voltage surge waveform for a typical isolated capacitor switching when the voltage is passing through peak value. The magnitude of the surge, its frequency and duration depend on C, L and R values dealt in detail later.

In the distribution system the capacitor banks are arranged in steps and switching operations are carried out to obtain the reactive power required to match with the prevailing load requirement so as to maintain the power factor at desired level. This necessitates parallel operations and capacitor bank arrangement in steps.

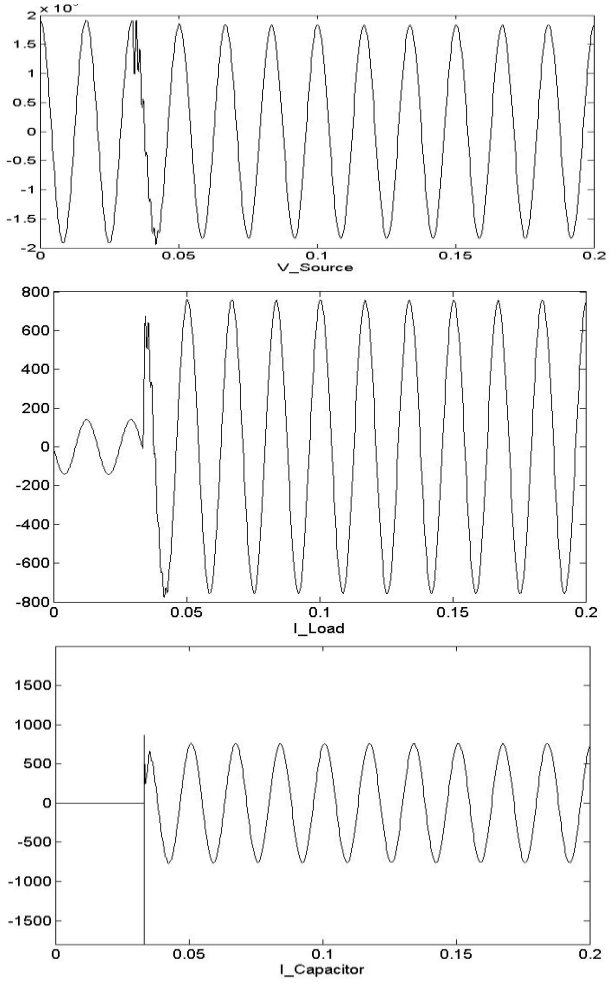


Fig.2 voltage surge for capacitor bank

A typical back to back switching arrangement is shown in fig.3, where in C1 and C2 are already in the circuit and C3 being switched on.

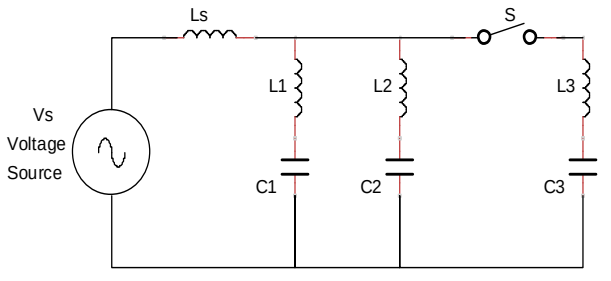


Fig.3 Back to Back switching of capacitor bank

Consider C1 and C2 are in energized condition and C3 with NIL / least charge is switched on. At, t=0+ a high frequency inrush current flows due to energisation of capacitor C3. This switching operation is associated with two types of transient oscillations, (i) very high natural frequency by which the C3 has to be brought to the same potential level of that of C1 and C2 and, (ii) with a considerable lower natural frequency by which all the three capacitors should be brought to the same potential level of the source. The first phenomenon given rise to large magnitude of inrush current at very high frequency and the second one is associated with relatively smaller transient current at low frequencies in KHz lasting for a longer duration.

The expression for the current at the instant of closing the switch is given by

$$i_2(t) = \frac{v_m \sin(\omega_2 t)}{z_T} \qquad \text{--------(1)}$$

$$\omega_2 = \sqrt{\frac{1}{LC}} = \sqrt{\frac{1}{L_0 + L_1}\left(\frac{1}{C_0} + \frac{1}{C_1}\right)} \qquad \text{-----(2)}$$

$$z_T = Z_0 + Z_1 =$$

$$\sqrt{(x_{L0} - x_{C0})^2} + \sqrt{(x_{L1} - x_{C1})^2}$$

(Neglecting resistance $R_0$ and $R_1$)

$$Z_T = x_{L0} + x_{L1} - (x_{Co} + x_{C1})$$

$$Z_T = 2\pi f (L_0 + L_1) - \frac{1}{2\pi f}\left(\frac{1}{C_0} + \frac{1}{C_1}\right)$$

$$Z_T = \omega(L_0 + L_1) - \frac{1}{\omega}\left(\frac{1}{C_0} + \frac{1}{C_1}\right) \qquad \text{--(3)}$$

Because of low impedance, the transient inrush current is very high. This high transient current circulates in the local parallel capacitor circuits and does not affect the rest of the circuit.

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*Capacitor Energising Transient:*

It is an established fact that when a capacitor bank is connected to supply, a high frequency and large magnitude transient current flows for a short period. The peak value of this inrush current for a single capacitor bank can be calculated using the formula.

$$I_{man} = 1.15 I_o \left(1 + \sqrt{\frac{shortKVA}{capacitorKVAr}}\right) \qquad \text{---(4)}$$

Where Io = nominal steady state power frequency peak current

The inrush current for purely reactive network has the

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following frequency

$$f = f_o \sqrt{\frac{shortcircuitKVAr}{capacitorKVAr}} \quad \text{------(5)}$$

Where $f_o$ = rated power frequency of the system.

At the instant of switching t = 0+ an uncharged capacitor exhibits zero impedance to the flow of current. The inrush current during switching of the single capacitor bank is limited by the series resistance and inductance of the circuit. The frequency of the large magnitude transient oscillatory current depends on the resistance, inductances & capacitance of the circuit. In the above formulae resistance is neglected.

As dealt above high frequency voltage and current oscillations occur during the energizing period. In respect of both single and parallel banks it is necessary to limit the voltage to less than twice, line to neutral value under normal switching conditions. The capacitors are capable of withstanding a high voltage in excess of two times rated value for very short durations. Thus in parallel operation of bank the following things must be given due consideration:

- Continuous voltage rating and transient voltage rating for short duration of time.
- Continuous current rating with adequate margin (1.43 times capacitor bank rating)
- Interrupting rating required for handling the short circuit current which may occur on capacitor side.
- Momentary current rating must be large enough to withstand both short circuit current during faults and inrush current associated with energization.
- Frequency of operating the switching device must be mechanically robust enough & electrically simple to withstand repetitive switching operations.

*Derivation of Inrush Current:*

Switching transient phenomenon for a capacitor bank is of considerable importance, particularly when contactors/circuit breakers are employed for switching operations. A typical capacitor switching ON operation is shown in fig.1 the highest magnitude of transient inrush current occurs when the contacts of capacitor switch are closed at the peak of voltage curve. The voltage and current relationship for this RLC circuit is

$$E_m \cos(\omega t) = iR + L\frac{di}{dt} + \frac{1}{C}\int idt \quad \text{.--(6)}$$

This integro-differential gives the current as a sum of two Steady state and transient component. The steady state components of the current is

$$I_s = \frac{E_m}{Z} \times \cos(\omega t - \phi) \quad \textbf{-----(7)}$$

Where, $E_m = \frac{\sqrt{2}E}{\sqrt{3}} = \sqrt{\frac{2}{3}}E$ ----(8)

Where, $E$ is line voltage

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

The maximum transient current occurs at a time $t_m$ and steady state current at this time $t_m$ is

$$i_s(t_m) = -\frac{E_m}{Z}\sin(\omega t_m)$$

This transient component of inrush current depends on the resistance and inductance of the feeder circuit and has a natural frequency $f_n$ given by

$$\omega_n = 2\pi f_n = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \quad \text{----(9)}$$

It is possible to adjust the resistance R such that

$$\frac{1}{LC} = \frac{R^2}{4C^2} \quad \text{----------(10)}$$

This resistance is called as the critical resistance given by

$$RC = 2\sqrt{X_L X_C} = 2\sqrt{\frac{L}{C}} \quad \text{------(11)}$$

For any other resistance R, the expression in terms of RC will be

$$R = nR_C = 2n\sqrt{X_L X_C} \quad \text{---------(12)}$$

Where, $n = \frac{f_n}{f_0}$, $f_0$ is rated frequency of system

The transient dies out if $R < R_C$ and will rise to a certain maximum value and dies out without oscillations if $R > R_C$. In case thyristors are employed for switching operations, it is possible to make it transient free. For this purpose, in the simulation network, two thyristors in anti-parallel mode are considered to carry out the switching either in positive half cycle or negative half cycle of the supply voltage. It is possible to have a control on switching instants. Simulation studies are carried out by using thyristors as switches in place of contactors and the switching transients for all the above cases are presented.

This expression is derived under the assumption that system equivalent resistance is negligible.

*Limiting the Transient Currents:*

To limit the magnitude, frequency and duration of the inrush current and frequency, following remedial measures are to be taken.

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- At the switching instant momentarily closing resistor may be inserted and then subsequently bypassed.
- By permanently placing a fixed reactance in the capacitor circuit. Remembering that the reactance will increase the energy loss in this system and also reduce effectiveness of capacitor.
- Synchronizing the closing of the circuit. In this case ensure that closing of the switch takes place at very nearer to zero voltage (zero voltage switching). This can be done more effectively with the help of thyristors as a controlled switche. A comparison of synchronized (thyristor) and non synchronized (contactors) transients are dealt in the subsequent sections.

## III TRANSIENT FREE SWITCHING STRATEGY:

The following five firing strategies are used in practice:

- Strategy A (Fig.4): Switch ON capacitor at negative peak of system voltage (15msec). when capacitor voltage is equal to system voltage (Vc=Vs) at negative peak of voltage with capacitor initially charged.
- Strategy B (Fig.5): Switch ON capacitor at negative peak of system voltage (15msec). When capacitor voltage is not equal to system voltage and capacitor not initially charged (Vc=0).
- Strategy C (Fig.6): Switch ON capacitor at negative peak of system voltage (15msec). When capacitor voltage is greater than the system voltage (Vc>Vs).
- Strategy D (Fig.7): Switch ON capacitor at system voltage is zero (10msec) and capacitor is not initially charged.
- Strategy E (Fig.8): Switch ON capacitor at instant (12msec) of system voltage and capacitor is not initially charged.

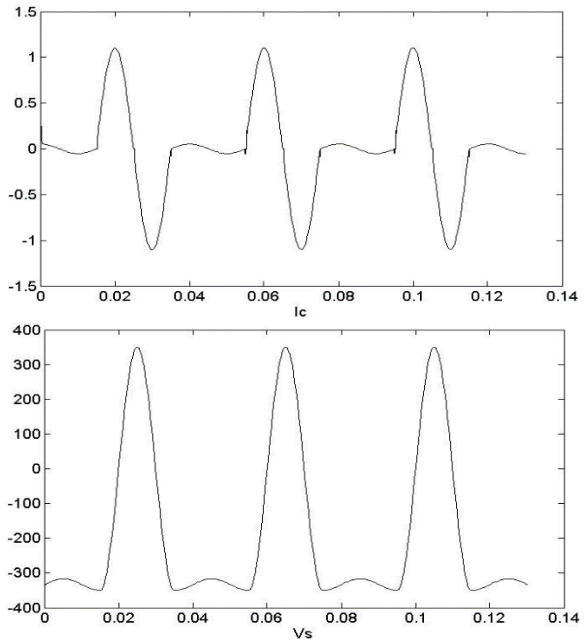

Fig.4 Strategy A

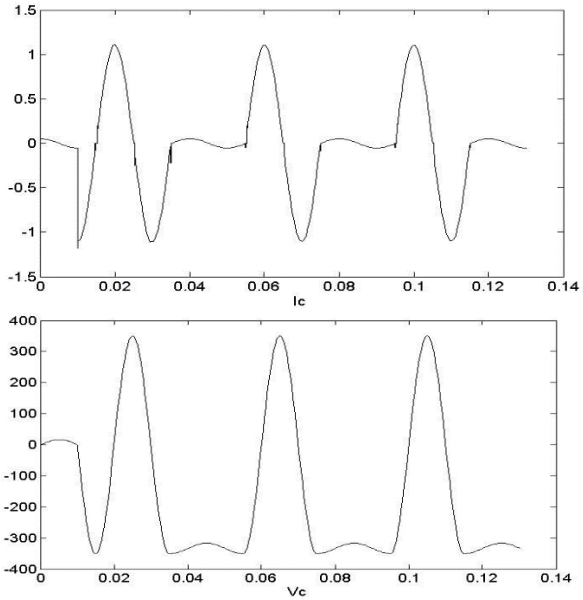

Fig.5 Strategy B

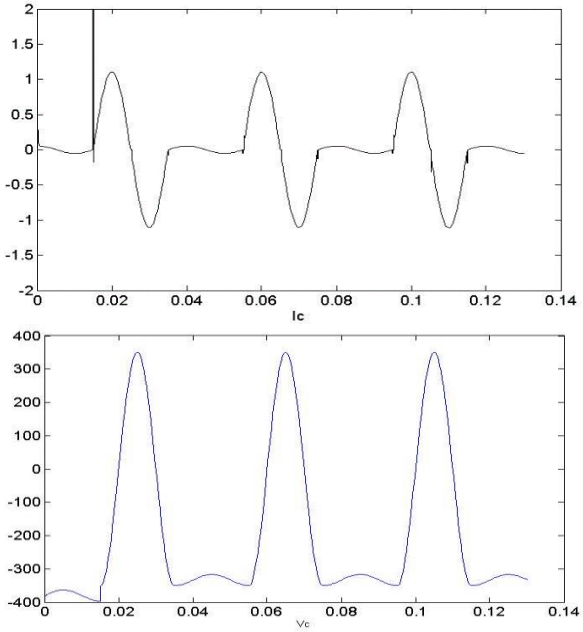

Fig.6 Strategy C

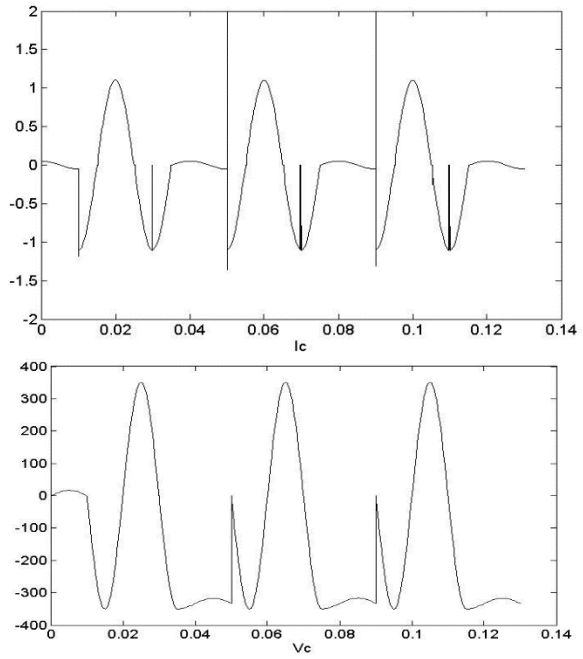

Fig.7 Strategy D

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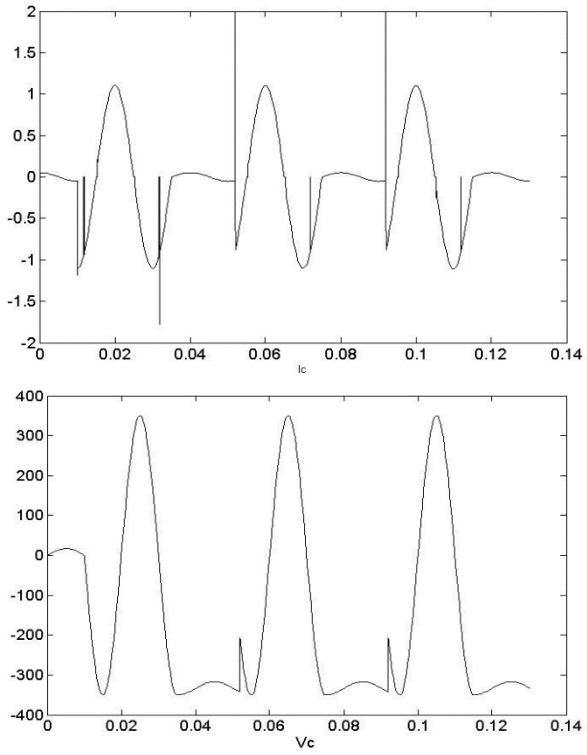


Fig.8 Strategy E

Transient free switching is obtained by switching the capacitors to the negative/positive peak of supply voltage and firing the thyristors at the negative/positive peak of supply voltage. Because of capacitor current is leading to voltage. If capacitor is switch on at negative/positive peak of supply voltage, at that time transient free switching can be take place

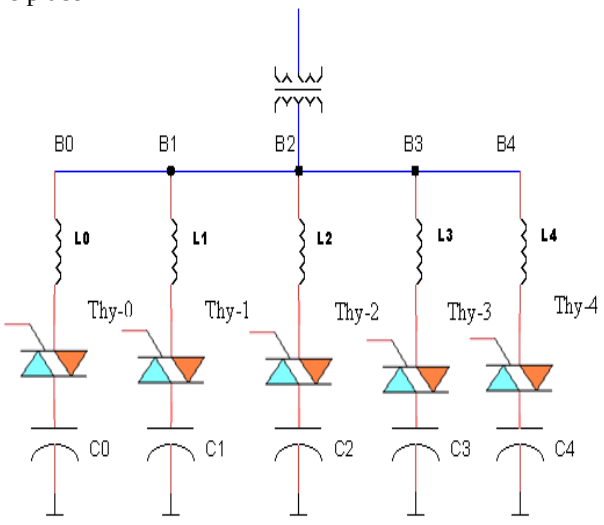


Fig.9 TSC with capacitor arrangement in binary sequential mode (TBSC)

The simplest configuration for an advanced shunt compensator essentially consists of the thyristor switched capacitor (TSC) bank with each capacitor step connected to the system through a thyristor switch. The capacitor bank step values are chosen in binary sequence weights to make the resolution small, known as Thyristor Binary Switched Capacitor (TBSC). If such n capacitor steps are used then 2n different compensation levels can be provided due to those many possibilities.

At the distribution transformer requiring total reactive power Q for improving the power factor from some initial value P.f1 to the desired value P.f2 at the load. This Q can be arranged in binary sequential 'n' steps, satisfying the following equation [1]:

$$Q = 2^nC + 2^{n-1}C + \ldots\ldots\ldots + 2^2C + 2^1C + 2^0C$$

In the standard configuration of TSC, a damping reactor is included to limit the di/dt on switching and to damp the switching transients that follow. An analysis of switching transients indicates that transient free switching can occur if the following two conditions are met:

a) The thyristor is fired at the negative/positive peak of voltage, and/or

b) Capacitor is pre charged to the negative/positive peak voltage.

The first condition can be met accurately by timing the control circuitry and the second condition is only met immediately after switching off thyristor. The configuration for five capacitor bank steps in binary sequence weight with thyristors switch and inrush current limiting reactors is shown in fig.9.

## IV Binary Current Generation:

The Fig.10 shows the binary operation of the TBSC compensator proposed in fig.3.1 The total compensating current from phase "R" (total ic), is being increased step by step. The capacitor currents from the branches Bl (ic1), B2 (ic2), B4 (ic4), and B8 (ic8) are shown in fig.3 respectively. In fig.3 the total compensating current for the phase "R" (total ic) is displayed (total ic=ic1+ic2+ic4+ic8).

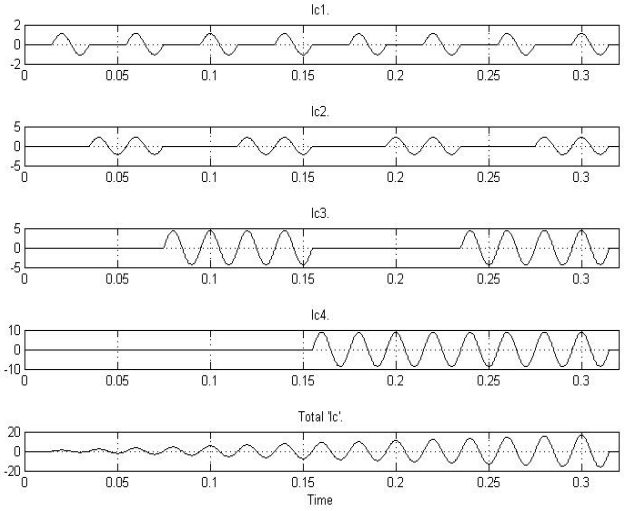


Fig.10 Compensating current for phase "R"

a) (Ic1) Current through B1 c) (Ic3) Current through B4
b) (Ic2) Current through B2 d) (Ic4) Current through B8
e) (Total 'Ic') Total Current through all branch.

*Voltage across each capacitor:*

The Fig.11 shows the voltage across each capacitor (C1, C2, C3, C4) bank at the time of binary operation of the TBSC compensator proposed in fig.9 Every capacitor is switched ON and OFF at negative value of the source voltage wave. This means the current starts from zero as a sinusoidal waveform without transient and or inrush problems.

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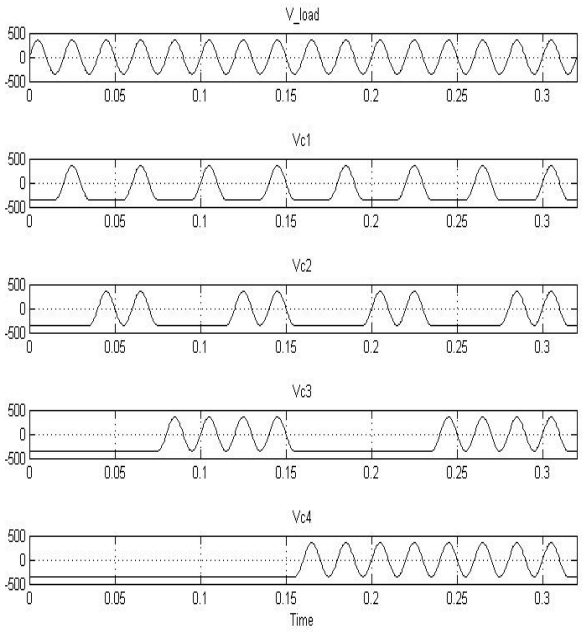


Fig.11 Voltage across capacitor ($Vc_1$, $Vc_2$, $Vc_3$, $Vc_4$).

## VI Conclusion

A topology using a TBSC has been presented. The TSC bank step values are chosen in binary sequence weights to make the resolution small. Current flowing through TBSC as well as source is transient free. Harmonic content in source current is negligibly small. By coordinating the control of TBSC, it is possible to obtain fully stepless control of reactive power. Also one can operate the system at any desired power factor. Proposed topology can compensate for rapid variation in reactive power on cycle to cycle basis, that is all most step-less compensation. Inrush current problems during connection and Outrush current disconnection are avoided.

Transient free switching is obtained by switching the capacitors to the negative/positive peak of supply voltage and firing the thyristors at the negative/positive peak of supply voltage.

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