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An Innovative Transient Free TBSC Compensator for Dynamic Reactive Load and Voltage Sag Mitigation

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ABSTRACT: 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. 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 [1]. 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. 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.

KEYWORDS: TBSC, transient free switching, binary current generation, switching strategies and thyristors.

I. INTRODUCTION

As there is reduction in loss with shunt compensation in the feeders, the efficiency increases and conservation of energy takes place. Besides the enhancement transformer loading capability the shunt capacitor also improves the feeder performance, reduces voltage drop in the feeder & transformer, better voltage at load end, improves power factor, improves system security with enhanced utilization of transformer capacity, gives scope for additional loading, increases over all efficiency, saves energy due to reduced system losses, avoids low power factor penalty, and reduces maximum demand charges. Power is the life stream of progress for any nation. Power systems have grown leaps and bounds in all the countries particularly during the last four decades. On account of the well established technical advantages and economic considerations, power systems are interconnected which makes then somewhat complicated in actual operation & control. The chief objectives of any supply undertakings are: to maintain continuity of supply with constant frequency and steady voltages of pure sinusoidal waveforms at various nodes, to reduce the overall cost of generation and conserve available resources, and to make the system highly secure & reliable. The basic problem is to produce both real & reactive powers most economically at appropriate locations for all the intervals of time and continuously match with the system requirements. In the process, number of regulating measures has to be taken, in order to keep the desirable voltage profile in the system, to reduce the reactive power flows in the lines and to minimize the network losses. Voltage control and reactive power compensation have remained the most engaging problems in

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power system engineering. Power is distributed through radial feeders, extending over wide spread areas. The LT consumers are of both 3-Ø and 1-Ø . The consumer end voltages are poor, the P.F. are very much lagging and network losses are high. On account of these reasons, lot of attention is paid to alleviate these problems in the distribution sector. Hence it has become necessary to give more emphasis on the distribution systems for maintaining good voltage at remote ends, minimize losses, improve the power-factors and conserve the energy. Hence to start with the problems associated with typical radial feeders are introduced in the next section. The basic distribution system diagram for typical feeders at a substation. It consists of three distribution transformers giving connections to various consumers through a common bus bar arrangement with bus couplers, so as to increase the reliability of service and flexibility in operations. Most commonly, the consumers are wide spread and the utility gives connection both for single phase and three phase loads. The electrical equivalent diagram of a typical 3Ø feeder on single phase equivalent. For short line below 50 km, line charging capacitance is neglected. For simplicity, it is conventional practice to represent load as constant power.

II. RELATED WORK

[1] Power utilities and their customers are often concerned themselves with three major problems that include increased power cost, reduced system capacity and deteriorated power quality. The distribution system is continuously subjected to changes in load will cause corresponding deviations in voltage at the load bus or the PCC. The loads such as repetitive welding operations, tractions, lifts, hoists etc will also result dips in rms voltage. Also there are other loads such as arc furnaces which draw a major portion of reactive power. For such loads the dominant reactive current needed results in significant voltage drop in the line impedance. Our focus of research in the thesis work is on a particular FACTS device – the adaptive static VAR compensator.

[2] The SVC is indispensable and based on proven technology for power factor correction and reactive power compensation. Traditionally SVC has been used as a shunt device that offers voltage stability and reactive power compensation to the load or at PCC. Since EPRI's (Electric Power Research Institute) release of FACTS strategies in 1987 SVC's have grown in popularity and are well established in power industry [11]. The SVC is regarded as the first in the series of FACTS devices. The Basin Electric Power Corporation installed the first SVC in Nebraska in 1977 [12, 13]. The simplest configuration for an advanced shunt compensator essentially consists of the thyristor switched capacitor 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. If such n capacitor steps are used then 2^n different compensation levels can be provided due to those many possibilities. It is important to ensure that static compensator steps are switched at appropriate times so that transients are minimized not allowed occurring. For both capacitors and inductor, the appropriate switching instants occur at the zero crossing of both current and voltage waves. 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. 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.

[3] Capacitors have a maximum theoretical switching in delay of one cycle, assuming that the capacitor is pre-charged to the incorrect polarity. The capacitor can be switched out in half-cycle. Capacitors are switched completely in or out of the circuit as and when needed. There are two control strategies for SVC's which are discussed in [12]. The first strategy is feed forward control, which repeatedly solves the model equations to determine the number of capacitor steps in the bank needed. The second strategy, feedback control is useful for closed loop control when minimization of error signal in the difference between defined kVAr and actual kVAr. Any change in the error signal will result in a change in susceptance of compensator. Because of closed loop operation, error signal always tracks to zero value. It is a continuous adaption of error signal towards zero [15]. A pioneering work in the Error Adaptive Power Factor Controller [EAPFC] was done by M. EI. Sharkawi [16, 17].

[4]These EAPFC's do not make use of an inductor branch as in SVC's but contributions to effective capacitor switching techniques are notable. The adaptive VAR compensation technology was developed at the University of Washington with sponsorship of Bonneville Power Administration (BPA) and Southern California Edison (SCE). The

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project was started in 1980 and ended in 1993. Subsequently related to this work number of papers were published [18]. The major work was carried in the design, development and implementation of 15 kV class of adaptive VAR compensator. The Adaptive Var Compensator (AVC), was solid state switched, binary stepped capacitor bank, used to compensate any rapidly changing reactive demand within one half cycle without introducing transients or harmonics [19]. The control strategy provided in this project is based on reactive power sensing and providing the compensation required thereby. It is possible to maintain the voltages within a desired value of least tolerance band. The control strategy is based on actual reactive power required by load to maintain the desired power factor.

[5] Hence voltage signal is not employed. In the light of all the developments that have been reported in the recent past, the desirable features for the controller to be developed are listed below which forms the main theme of Thesis work under taken. Any one of the modes can be implemented at a time and can be controlled by specified time scheduling [19]. The potential applications of AVC are at load end or at system level compensation. The load end application includes those requiring rapid compensation such as lumber mills, rock crushing plants, steel mills, elevators, arc furnaces, pumps, electric railways. The distribution system application includes reactive VAR compensation, enhancement of voltage regulation, prevention of voltage collapse, released system capacity, reduction in line losses and increase in efficiency. The innovative and useful design of the AVC has resulted in commercialization of the device and reported in three US patents. All the above referred controllers do not have any reactor part as such. To maintain the power factor at unity, binary steps required are high to reduce the resolution.

[6] But still these APFC's are robust, controller catering to the sudden changes in reactive power demand and reduce voltage flicker. In 1990, number of papers got published on microcontroller (Microprocessor) based static VAR compensator [20, 21]. Also gives the details of open loop control strategy of SVC, while in hardware SVC model was developed for laboratory experiments. The model consists of FC-TCR scheme. The control strategy used was based on PD & PID. The project focused specific inductor control through developing a prototype model. While in fuzzy logic control scheme was used. The goal of this fuzzy controller was to provide maximum damping and improve stability in the power system. An attempt is made to briefly outline the developments that took place particularly in recent years with regard to the application of static Var compensation in the distribution systems. Number of improvements has been brought out through intensive work by many authors world over. So much importance is given to this aspect due to the necessity to meet the consumer requirements. As can be expected, there does not exist a universal solution to mitigate all the problems encountered and the behaviour of a composite load is somewhat complicated. It depends on the composition of loads, configuration of network, short circuit level at PCC, loading pattern and the controllers used. However, the desirable features of a controller that can be used for a typical SVC employed in either H. T. or L. T. systems are mentioned in brief below.

[7] Reactive power compensation and its effective management are essential to improve the performance of A. C. power systems. It is viewed from load compensation, voltage support and improving the quality of power supply. Both the series and shunt VAR compensation are used for modifying the natural electrical characteristics. Series compensator modifies the transmission system parameters to improve the power handling capability. On other hand, the shunt compensator changes the equivalent impedance in the distribution system. Conventionally, rotating synchronous condensers, fixed or mechanically switched or thyristor switched capacitors in conjunction with reactors are used for compensation. Of late static VAR compensator (SVC's) consisting of thyristor switched capacitor (TSC's) and thyristor controlled reactor (TCR's) are widely used to provide the required reactive power, both leading and lagging. The recent development in power electronics, powerful analytical tools, advanced microcomputer technologies for control have enabled the power system engineers to implement fast reactive static compensators capable of generating or absorbing reactive current components. A wide variety of shunt compensators are developed over the years with fast response and high reliability leading to new concepts in the operation of power system. A comparative statement of compensators in vogue is reproduced in table 1 from reference (Varma) for ready information. This gives a bird's view of the compensation technologies and reproduced here for the sake of completeness.

III. MOTIVATION

Most loads are of inductive in nature due to which the power factor is lagging, and the voltage becomes low at full load, hence there is a necessity to provide reactive power compensation, to improve the power factor and give a boost

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to the voltage. The role of a capacitor is illustrated. The initial power factor is cos($Ø_1$) and with compensation the power factor is improved to cos($Ø_2$). In the process for a given active power P_1, the KVA demand gets reduced from S_1 to S'_2. This facilitates the scope for additional loading up to P_2 giving raise to effective utilization of the transformer capacity.

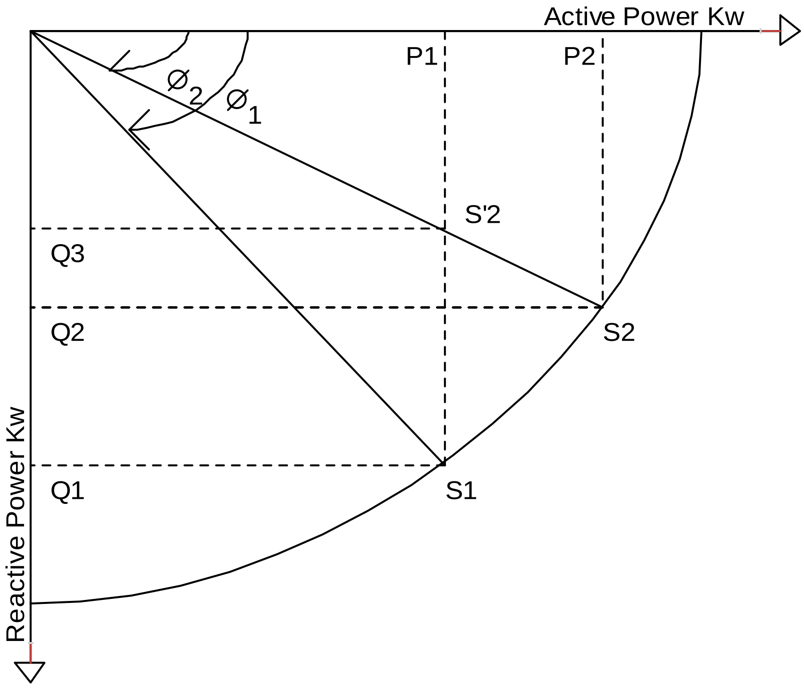

Fig. 1 Reactive power compensation on a feeder

Apparent powers S_1 and S_2 in are held constant for varying power factor and hence represented as circle with corresponding real powers P_1 and P_2. Q_3 represents reactive power for P_1 at new power factor cosϕ_2.

IV. OBJECTIVES

The purpose of this work is to present a new topology for a var compensator, which eliminates the problems already mentioned. This topology has the following distinctive characteristics [7, 8]

1. It maintains the power factor at the PCC to any specified value.
2. It compensates for rapid variation in reactive power or voltages.
3. Maximum compensation time is 20 msec.
4. No transients or harmonics are allowed to be present due to fast selective instants of switching in well co-ordinate manner.
5. It is adaptive in the sense that the amount of the compensation is determined and provided on a cycle by cycle basis.
6. It can compensate each phase independently which makes ideal for unbalanced systems.
7. Capacitors are sized in binary sequential ratio for minimum size of switching steps.
8. The control strategy is error activated to match with the load reactive power for the chosen time interval.
9. It eliminates possible over compensation and resulting leading power factor.
10. It is flexible to choose required number of steps as per the resolution.
11. Resolution can be made small with more number of steps.
12. Simple in principle, elegant in usage and of low cost.
13. Possible to incorporate the idea presented in the controllers for large size transformers at substations.

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V. PROPOSED SYSTEM DESIGN

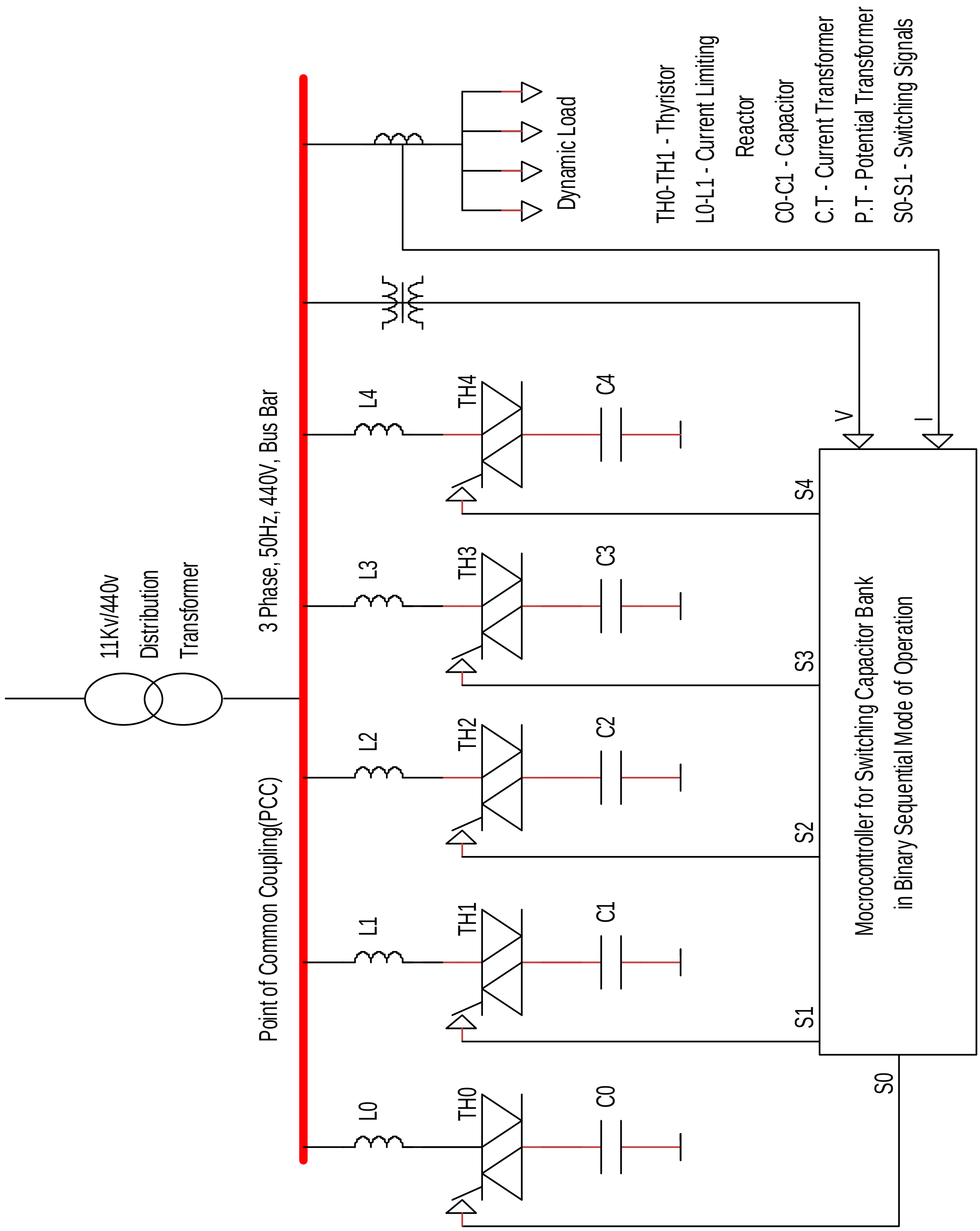

Fig 2 Block Diagram of Proposed Work

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Capacitor is the most indispensable static device in a power system. It can be connected either in series form or shunt form for power frequency applications. Below 650 volts the capacitors are categorized as LT and above 650 volt as HT. It is possible to design and manufacture capacitor units of standard sizes and banks can be formed with series parallel combinations of units for the required capacities. Capacitors are relatively cheap; no foundations are required for installations, most efficient due to very low losses (0.3 to 1.5% of the rating), least maintenance and incur low annual charges. Their limitations are: incapable of providing step less variation in Q, the reactive power is proportional to the square of mains supply voltage, associated with switching transients and resonance problems.

Since 1940's the voltage stress has increased from 18 volts per micron to 70 volts per micron, loss got reduced from 0.5 % to 0.01%, the size of individual unit from a few KVAr up to 600 KVAr, voltage few volts to 11 KV and the volume got reduced from 600 cm^3 per KVAr to about 100 cm^3 per KVAr. These figures are indicative of technological advancement in the manufacture of capacitor units for both LT and HT applications. The LT capacitors are manufactured with metalized poly-propylene (MPP) in either three phase single units or single phase units. The capacitors are designed and built for delta connection in LT applications. On the other hand they are connected in star for HT applications. HT capacitors are manufactured making use of bi-axially oriented poly-propylene (BOPP) of small sizes. They are connected in series-parallel combinations forming banks to suit the voltage and KVAr requirements.

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. A capacitor bank can be formed with capacitors in steps, more number of steps gives reduced resolution but the cost of switch gear will increase in order to get a continuously variable reactive power. The LT capacitors employed for experimental set up are of the following rating:

Table 1 Capacitor bank value:

Capacitor Bank	VAr Value	Microfarad Value
C0	100	10µf
C1	200	20 µf
C2	400	40 µf

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.

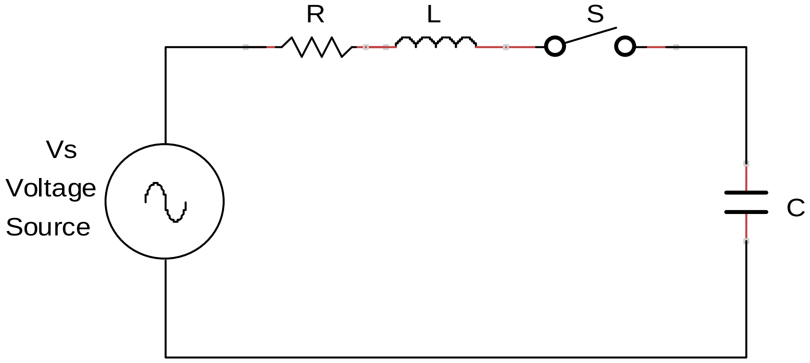

Fig. 3 Energizing of capacitor through switch

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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 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. It 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.

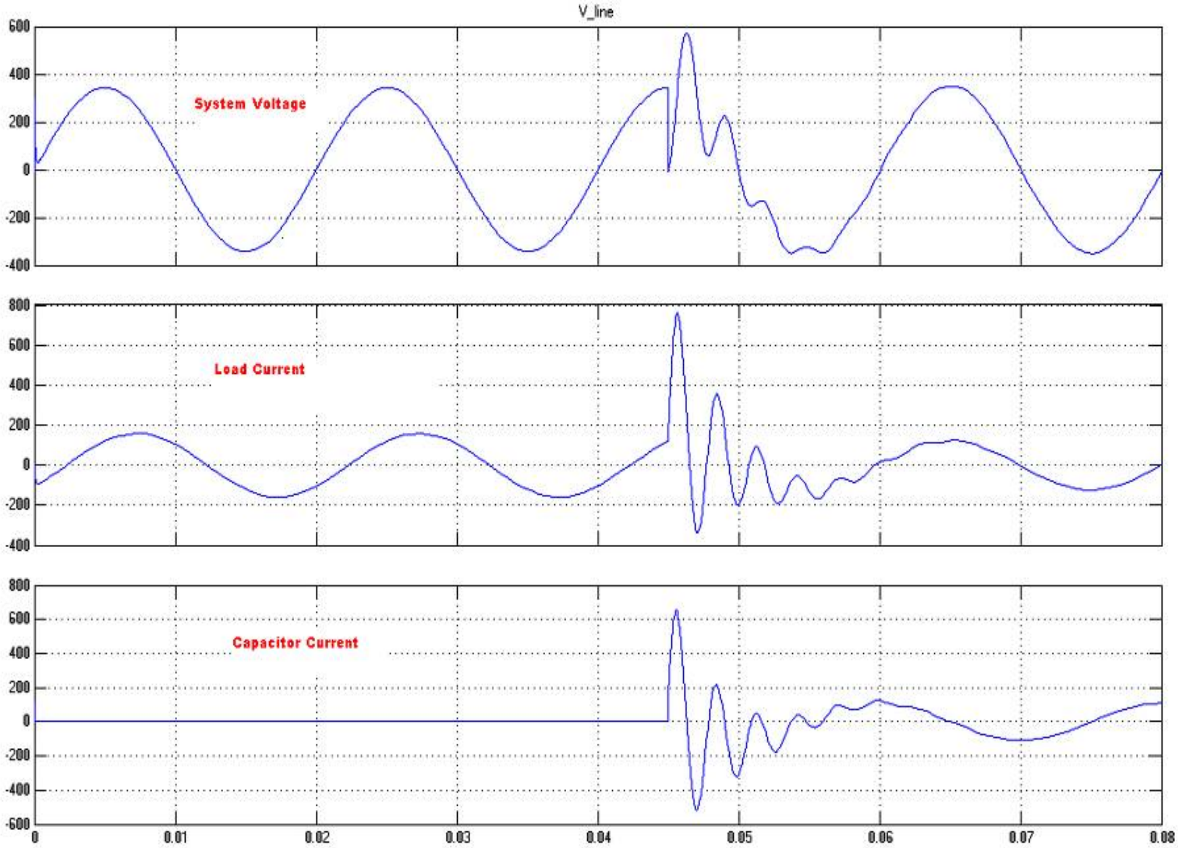

Fig. 4 voltage surge for capacitor bank

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. 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 [22].

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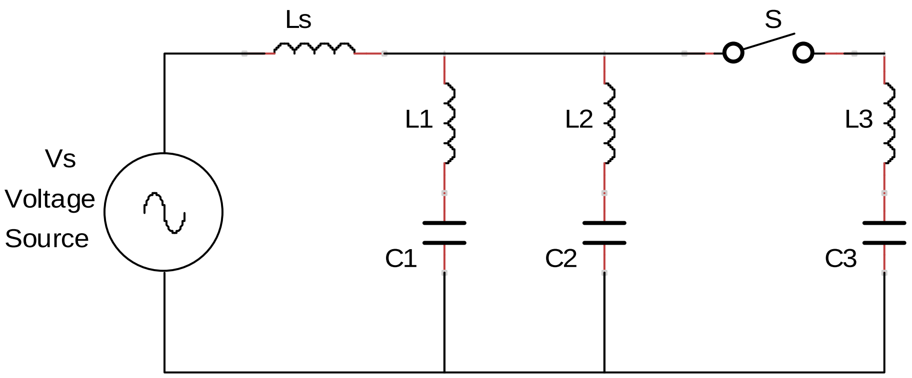

Fig. 5 Back to Back switching of capacitor bank

Consider C_1 and C_2 are in energized condition and C_3 with NIL / least charge is switched on. At, $t=0^+$ a high frequency inrush current flows due to energisation of capacitor C_3. This switching operation is associated with two types of transient oscillations, (i) very high natural frequency by which the C_3 has to be brought to the same potential level of that of C_1 and C_2 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 objective of this dissertation is to present "An Innovative Transient Free TBSC Compensator for Dynamic Reactive Load and Voltage Sag Mitigation" scheme for reactive power compensation and power quality improvement in power system.
This synopsis presents a topology. The proposed scheme consists of Thyristor Switched Capacitor (TSC) banks in binary sequential steps known as Thyristor Binary Switched Capacitor (TBSC) [25, 26]. This TBSC facilitates step-less control of reactive power closely matching with load requirements so as to maintain desired power factor. The proposed topology has following distinctive features [7]:

1. TSC (Thyristor Switched Capacitor) banks are arranged in Binary sequential steps to provide almost continuous reactive power compensation.
2. 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.
3. It compensates for rapid variation in reactive power.
4. Reactive power compensation is achieved in cycle by cycle basis. That is step-less compensation.
5. **Inrush** current problems during connection and **Outrush** current disconnection are avoided.
6. 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]:

   a. $\mathbf{Q = 2^{n}C + 2^{n-1}C + \ldots\ldots\ldots + 2^{2}C + 2^{1}C + 2^{0}C}$

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VI. SIMULATION RESULTS

1. MATLAB Simulation model of single phase TBSC compensator:

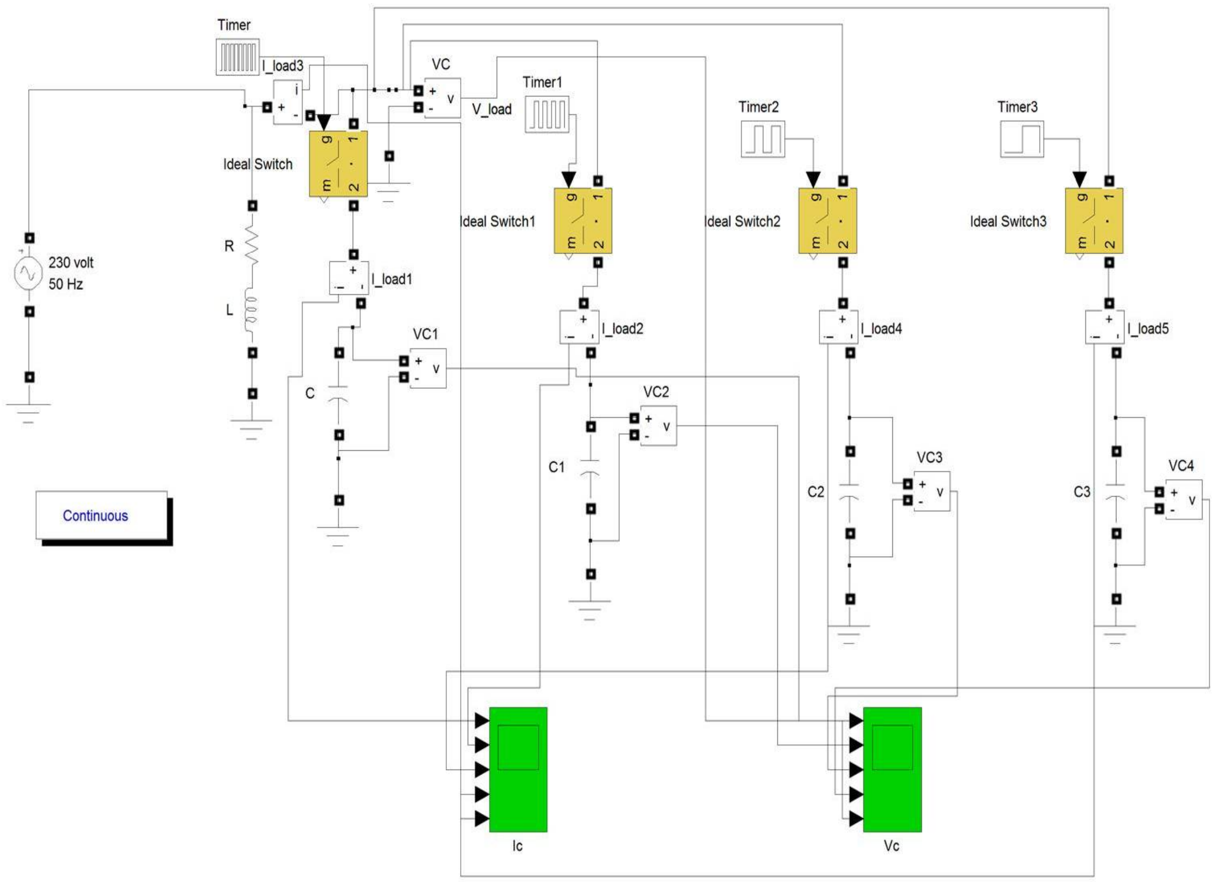

Fig 6 Open loop Simulation model for single phase system

Above fig shows the TBSC compensator with four capacitor bank, load, switch, pulse generator and with single phase 230volt AC supply. This model specially designed for to generate binary compensating current. In this model value of capacitor is chosen in binary sequence and the values are 1µf, 2 µf, 4 µf and 8 µf, therefore due to this value and switching pulse step less control and transient wave form is obtained. To obtain transient free switching I m chosen one instant that is negative peak of supply, at this instant capacitor current is zero. If we switch capacitor and off at this instant then the there will be no transient occurs across switch. It shows the binary operation of the TBSC compensator proposed. 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 the total compensating current for the phase "R" (total ic) is displayed (total ic=ic1+ic2+ic4+ic8).

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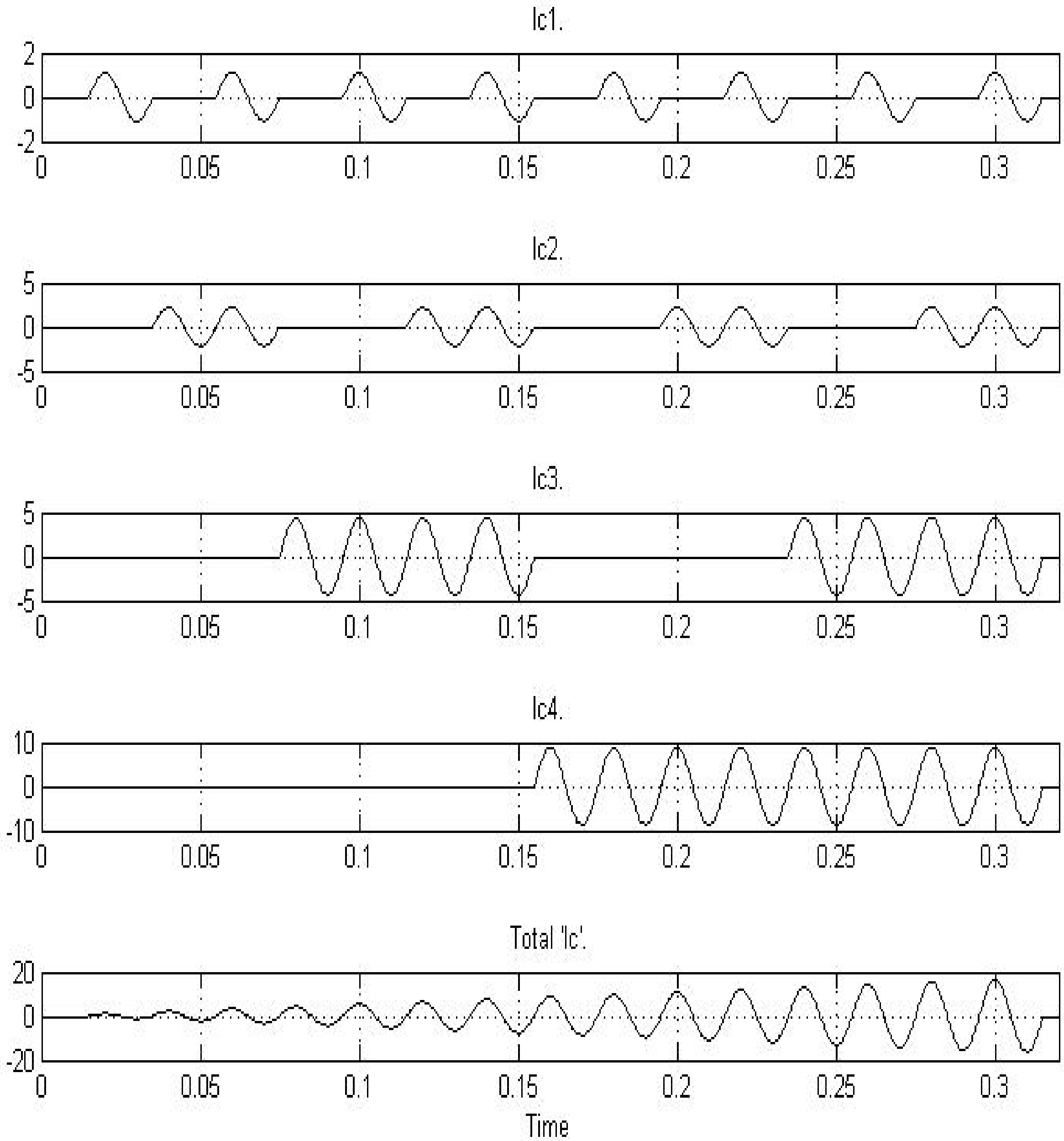

Fig 7 Compensating current for phase "R"

a) (Ic1) Current through B1 c) (Ic3) Current through B4

b) (Ic2) Current through B2 d) (Ic4) Current through B8

It shows the thyristor switched capacitor in binary sequential mode with four steps. The objective in the switching strategy is to be developed through the simulation, to make the switching operation transient free for all combinations. The sequence employed for switching operation is as follows:

Step - 1	:	Capacitor C_1 is brought ON for one cycle and OFF for one cycle.
Step – 2	:	Capacitor C_2 is brought in when step 1 is OFF and kept ON for two cycles.
Step – 3	:	Capacitor C_3 is switched ON after 1 and 2 are kept ON for four cycles.

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Step – 4 : Capacitor C_4 is kept ON at the instant when 1, 2, 3 are OFF and kept ON for eight cycles.

The simulated results are shown for the various currents that are flowing in branches C_1, C_2, C_3 and C_4. And the total system compensating current

$I_{Total} = I_{C0} + I_{C1} + I_{C2} + I_{C3}$ .... [6.9]

is shown in Fig.

This simulation experiment gives smooth transition to make the resulting system compensating current practically transient free. In case the above switching conditions are completely satisfied, the inrush current limiting inductor L may be minimized or even eliminated. The above steps indicated for switching operation are incorporated version of the mode of switching reported in reference [1]. Absolutely transient free switching operation could be achieved as can be seen from the aggregate waveform. The transition is smooth with no device being subjected to undue stresses. The Fig. shows the voltage across each capacitor (C_1, C_2, C_3, C_4) bank at the time of binary operation of the TBSC compensator. 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.

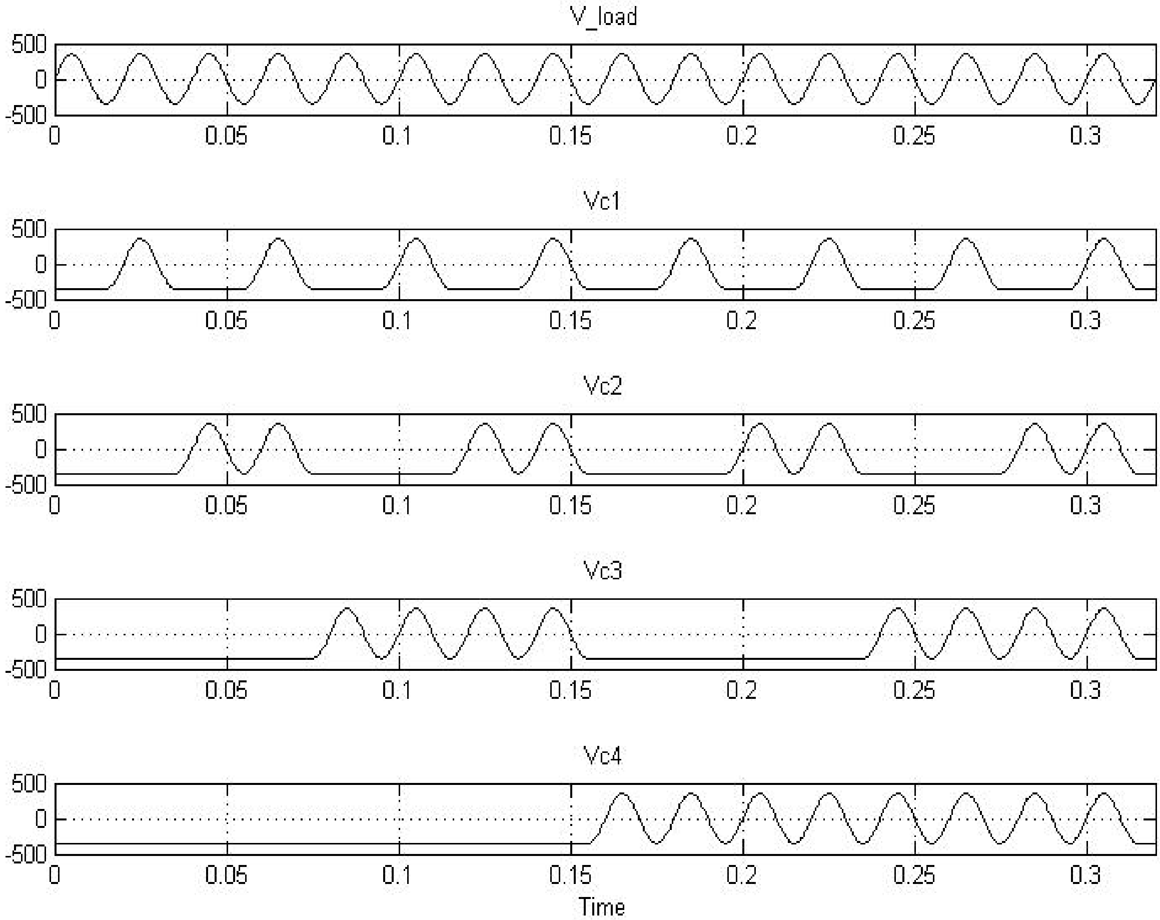

Fig 8 Voltage across capacitor (Vc_1, Vc_2, Vc_3, Vc_4).

2. MATLAB Simulation of TBSC Compensator for fast varying dynamic load:

Data used in Simulation:-

a. Source:-
Voltage V = 400 V, Rs = 0.0287Ω, Ls = 0.20471mH.

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b. TBSC banks:-
Five TBSC banks are used in the simulation whose values are shown.

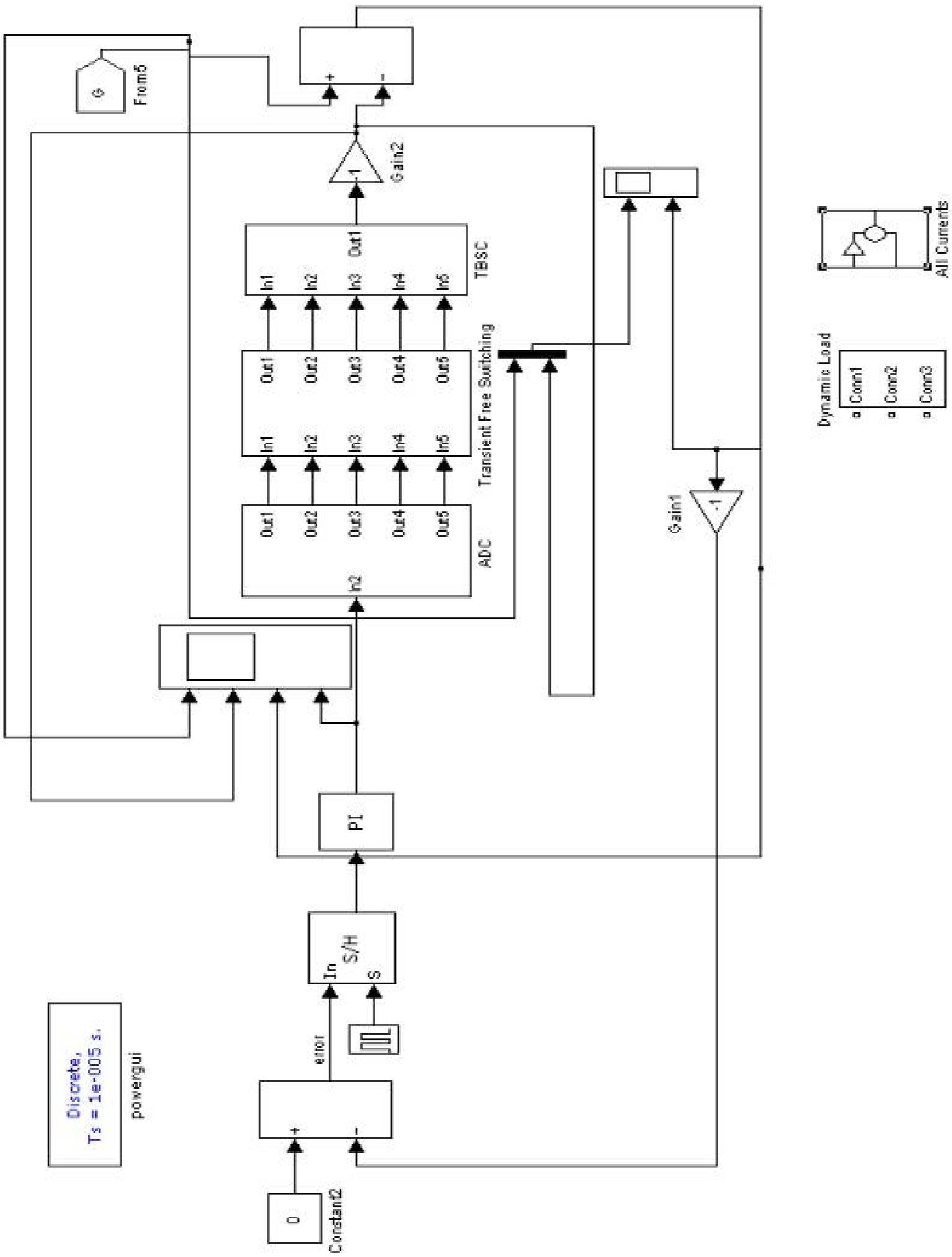

Fig 9 Closed loop Simulation model for three phase system

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Table 2 Values of five TBSC banks

Sr. No.	Q (in KVAR)	C (in µF)	L (in mH)
1.	2.5	45	0.32
2.	5	90	0.16
3.	10	180	0.08
4.	20	360	0.04
5.	40	720	0.02

Continuously changing reactive power, Q_L is obtained by simulating three phase dynamic load. The nature of load variation is as shown.

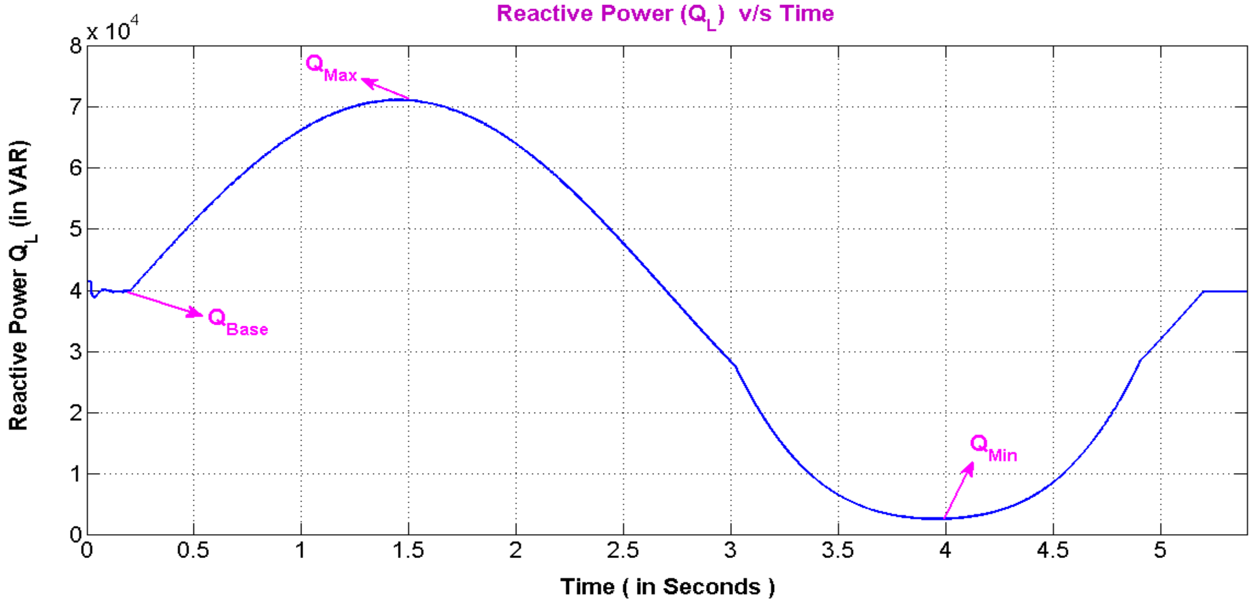

Fig.10 Simulation of three phase dynamic load

Minimum reactive power Q_{min}, maximum reactive power Q_{max}, and base reactive power Q_{base} can be varied by changing the parameters of three phase dynamic load. In all simulations Q_{Ref} is set to zero since it is assumed that desired P.F.is unity at all times. Discrete PI controller with K_P = 0.565 and K_I = 25 is used. 5 bit ADC is used in simulation. Parameters of Three-phase dynamic load block are adjusted in such a way that Q_L varies continuously from $Q_{Min.}$ = 2.5 KVAR to $Q_{Max.}$ = 77 KVAR with base load $Q_{Base.}$ = 40 KVAR. This variation takes place in five seconds. Waveforms of load reactive power Q_L, reactive power given by TBSC, $Q_{comp.(TBSC)}$ and actual reactive power Q_{Actual} at PCC.

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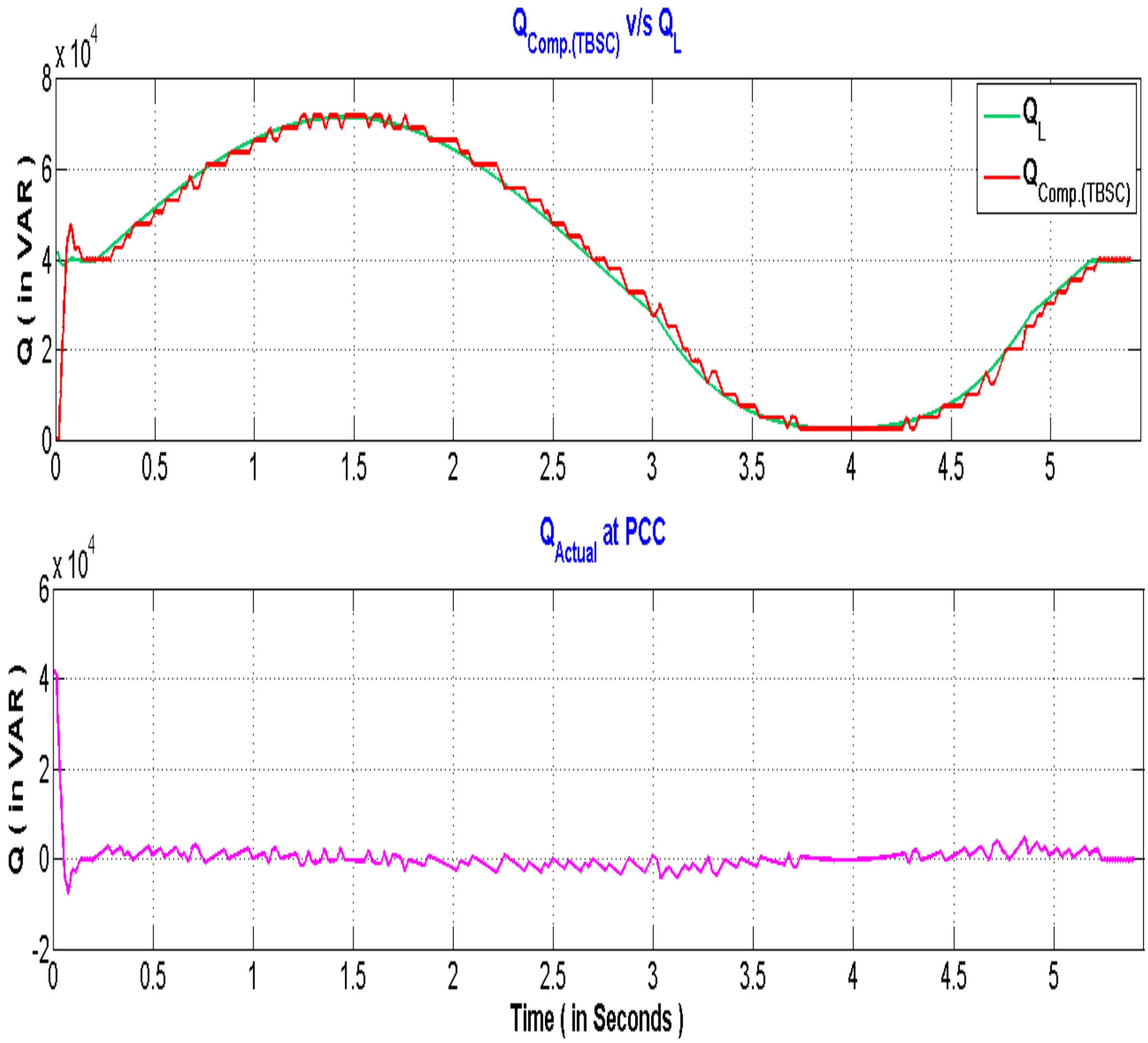

Fig.11 Simulation Result of TBSC operation

From simulation results it is seen that $Q_{comp.(TBSC)}$ closely follows Q_L, and actual reactive power Q_{Actual} at PCC is approximately +500 to -500 VARs at all discrete switching instances. The small error is due to the binary switching arrangement of TBSCs. These errors can be minimized by adding more number of capacitor banks in TBSC.

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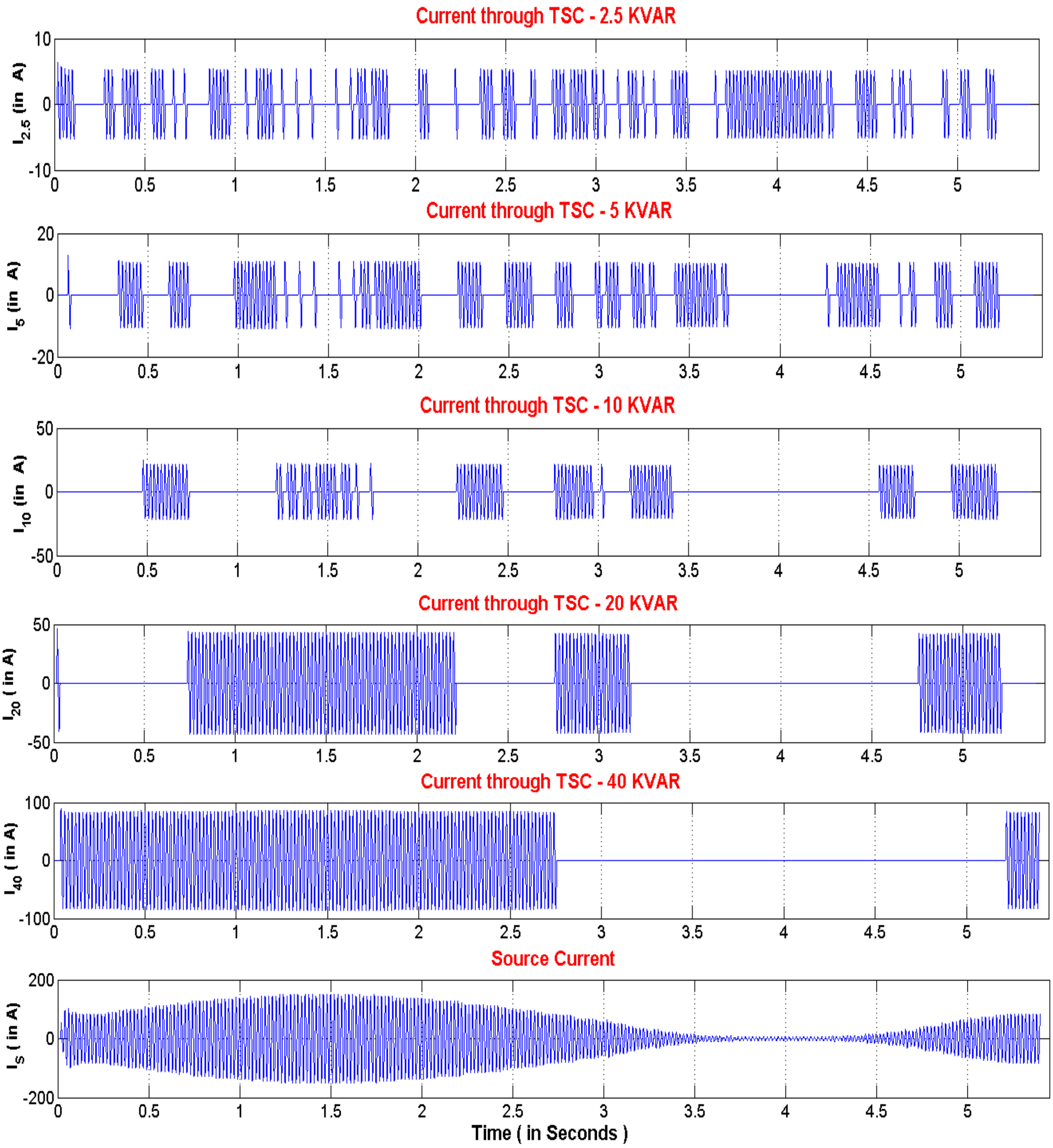

Fig.12 Current waveforms through all TBSC bank and source (of R phase only)

VII. 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

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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. An attempt is made through this work to develop a scheme with thyristors to reduce the cost by avoiding IGBT's and IGCT's, technically sound with reliable performance during both steady state and transient conditions, suitable for rapidly changing / fluctuating loads such as arc furnaces, tractions loads, welding equipment's etc., and self-regulating operations are practically both transient and harmonics free. The scheme developed is most suitable for highly nonlinear, fluctuating and harmonic generating loads. It gives following benefits:

Future Scope:

1. Fast varying dynamic reactive power compensation.
2. Voltage sag mitigation at the time of Induction Motor starting.
3. Also it can be used for, at the time of long transmission & high rating of transformer charging.
4. Also it can be used for, to avoid resonance condition

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