CHAPTER FIVE

NOVEL CONCEPT OF REACTIVE POWER COMPENSATION WITH ACTIVE POWER BALANCING

5.1 INTRODUCTION

Most of the installations and distribution networks suffer from unbalanced active as well as reactive power drawn by connected loads. This reduces life of the transformer drastically. This has led to evaluation of method for dynamic reactive power compensation with source side active power balancing, against the described unbalanced load currents. This chapter, initially highlights the need for the load kW balancing from source side. It then introduces the developed concept of reactive power compensation with active power balancing in three-phase systems. It then introduces simulations in MATLAB for achieving the load active power balancing with reactive power compensation. Further, the algorithms developed and associated simulation results are given.

5.2 NEED FOR LOAD KW BALANCING

Considering the last three decades, the industrial load & application demands have widely grown in terms of speed, accuracy, controllability, dynamic response and features. Low Tension (LT) distribution and High Tension (HT) distribution have also been facing different challenges. The LT distribution suffers from unbalanced loads resulting in failure of Distribution Transformers (DTs). The load dynamics may still not be so severe. However, when several DT's are supplied by one substation, the load dynamics seen by the substation sees a multiplying effect and becomes quite severe. The severity is then automatically reflected on the transmission line supplying power to the particular substation. On the other side, when it comes to the HT consumers, the internal distribution and type of loads employed decide the dynamics that gets transferred to the power coupling point.

Closely looking at each LT substation and a single HT consumer, the reactive power dynamic compensation provided by conventional solutions like capacitor banks, or Thyristor Switched Capacitors (TSC), normally results in over or under compensation based on the load dynamics. Hence, when the load dynamics is very fast (this perhaps is because of single load itself or a combination of multiple loads), active converter (Voltage Source Converter : VSC), based solution like STATCON can facilitate reactive power compensation. Close observation of this

application also reflects that while poor power factor of operation has been reducing effective kW delivery from the given distribution node, serious challenges are also faced, especially in rural-agricultural sector electricity distribution, where the loading pattern at a given point of time, on the given three phase distribution transformer is also not uniform. This unequal loading also restricts the maximum kVA which can be utilized from given installed transformer, as the peak current demand on particular phase do restricts the other phase being under loaded.

5.3 CONCEPT OF REACTIVE POWER COMPENSATION WITH LOAD KW BALANCING

Details of three-phase STATCON catering to balanced loads while the single-phase STATCON catering to single-phase loads and unbalanced three-phase loads, (with individual phase incorporating a single-phase STATCON) are already covered in chapter 3.

This concept basically extends the VSC (Voltage Source Converter) – STATCON design, which can dynamically compensate reactive power to now also balance active power drawn from the source and thereby allows unity power factor operation at the input supply within its capacity. As explained earlier, STATCON can achieve these demands, by properly adjusting the angle between the system voltage and STATCON voltage, which gets generated based on compensation demand. For addressing the load requirements beyond the declared capacity/ ratings of the STATCON, the STATCON units can be paralleled.

The concept has potential application for power distribution using Distribution Transformers (DT's), which face unbalanced load conditions very often. It then helps the DT's to operate close to unity power factor. This results in optimal use of capacities of the DT's. It should be noted that when STATCON gives balance reactive power compensation, the second harmonic current flowing in dc side capacitor bank is close to zero. However, when unbalance currents are compensated (active as well as reactive), the dc side second harmonic can vary and assume large values. Thus, the dc side capacitor value needs to be properly designed to accommodate the maximum second harmonic ripple current and its voltage ripple. Figure 5.1 below shows the schematic of such a solution.

3 Phase AC Supply

Balanced load delivery

Unbalanced load

Non-linear Load

i_{s1}

i_{L1}

i_{c1}

wL_b

V_{dc}

- Absoprtion of unbalanced kVAR
- Redistribution of unbalanced kVAR with total kW absorbed equal to zero
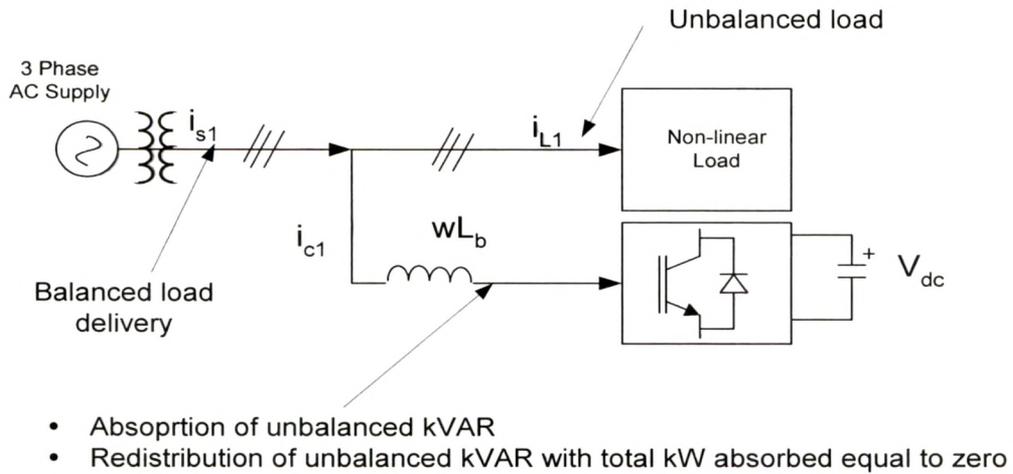
Fig. 5.1 Reactive Power Compensation with load kW balancing

Subsequent sections now describe the simulation of above model in MATLAB, simulation results and algorithm developed.

5.3.1 BASIC EQUATIONS FOR LOAD KW BALANCING
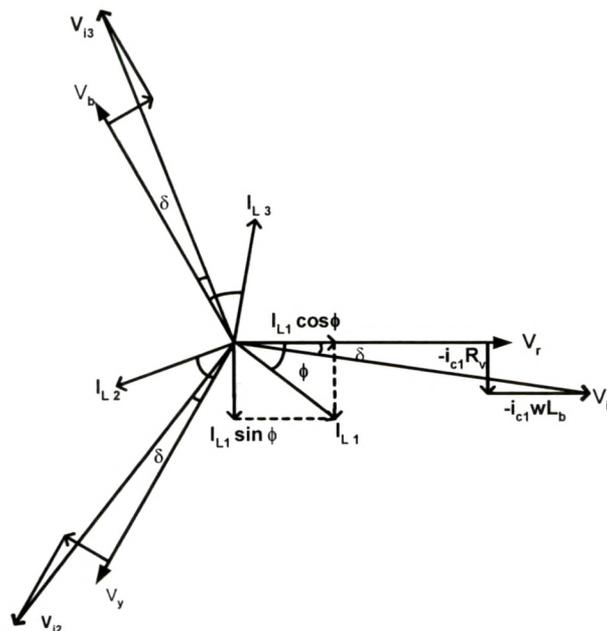
Fig. 5.2 Vector diagram for the STATCON operation for kW balancing

Consider the vector diagram as shown in fig. 5.2, which is used for simulation. Fig. 3.9 and 3.10 in chapter 3 also needs to be kept in reference. It is necessary to look at the basic equations of the active converter or STATCON. The fig. 5.2 shows the load currents i_{L1}, i_{L2}, and

i_{L3} drawn at given power factor angle "ϕ". STATCON draws compensating currents as i_{c1}, i_{c2}, and i_{c3}. I_{cm} designates the peak values. L_b is the boost inductor, R_v is the per phase dynamic resistance seen by the STATCON (mainly includes the loss component of STATCON). Instantaneous supply phase voltages are called as v_r, v_y, v_b and the instantaneous fundamental voltage component of converter (STATCON) switching input voltages are called as v_{i1}, v_{i2}, and v_{i3}. These are the voltages, which need to be computed to achieve the necessary compensation. From the vector diagram in fig. 5.2, these voltages can be calculated as under on a per phase basis. It is done here considering R phase and capacitive or inductive power drawn by the STATCON. It has to be done for all the three phases at the same time.

Capacitive mode

$$v_{i1}= (V_m + I_{cm} {}^*wL_b) \sin wt + (1/6) {}^* (V_m + I_{cm} {}^*wL_b) \sin 3wt -- (E) \cos wt \qquad (1)$$

Inductive mode

$$v_{i1}= (V_m -- I_{cm} {}^*wL_b) \sin wt + (1/6) {}^* (V_m -- I_{cm} {}^*wL_b) \sin 3wt + (E) \cos wt \qquad (2)$$

Here V_m is peak supply phase voltage and E ($=I_{cm}{}^*R_v$) is the dynamic resistance voltage drop. This includes the dynamic loss in the devices also. Third harmonic injection (1/6th of fundamental) is considered for getting more fundamental voltage (only sine component is considered and not the cosine component, which does not contribute much towards the vector displacement).

5.3.2 STEPS FOR THE BASIC CONTROL FUNCTION

1. Sense the individual phase load current and supply voltage

2. Calculate current displacement from the supply phase voltage and then the power factor of the load.

3. Calculate the reactive power component of the load current ($I_L \sin \Phi$). The compensating current to be drawn by STATCON will now be $-(I_{L1} \sin \Phi)$.

4. Calculate the active power components ($I_L \cos \Phi$) of individual phase and find its average value. Let it be called as Iact/avg. The active current to be drawn by STATCON for compensation (so that source active currents will be equal) will now be Iact/avg - $I_L \cos \Phi$

5. The total compensation current now will be $[-I_{L1} \sin \Phi + Iact/avg - I_{L1} \cos \Phi]$. These two can be added vectorially to get the final compensation current to be drawn by the STATCON. The compensating currents will have to be calculated for all the three-phases simultaneously. The peak value of the currents in each phase is entered in equations (1) or (2) (based on whether the reactive current compensation is capacitive or inductive) to solve for the fundamental component v_{i1} (or v_{i2} or v_{i3}). The error E in equation (1) or (2) is obtained from PI controller. Output of the PI controller is proportional to the DC voltage reference and the actual output dc voltage.

5.3.3 BASIC SIMULATION MODEL

Three-phase reactive power compensation with active power balance, on the basic three-phase STATCON model is simulated in the MATLAB. The basic specifications used during simulation are as follows:

- Total Reactive Power Which can be supported by STATCON/requirement: 61.098 KVAR

- Supply Voltage: V_L=415V

- STATCON Current required: I_{ss}=85A

- DC Bus Voltage: 800V

- Boost Inductor:1.65mH.

- DC Capacitance:4700uF

- Carrier Frequecy:2800Hz

- Modulation Index Range m_a=0.4 to 0.95

- Number of Phase:3

- Supply Frequency=50Hz.

The System is simulated for three scenario as below:

1. Qstat = Qload (STATCON Capacity same as load demand)

2. Qstat < Qload (STATCON Capacity lesser then load demand)

3. Qstat > Qload (STATCON Capacity higher then load demand)

Source KVA rating conceived is 80KVA. Basic assumption for working is that, STATCON will first compensate the reactive power demand of the load and then excess of its devices capacity (as decided by STATCON capacity) then is used for active power balance.

To address above cases considering above defined parameters, load conditions as defined in table 5.1 are used in simulation.

Table 5.1 Simulation Parameters for Active KW balancing through STATCON

	Qstat = Qload	Qstat<Qload	Qstat>Qload
Vrms (source)	239.6003617	239.6003617	239.6003617
Q(KVAR) demand	61098.09224	75000	54000
S(KVA)source rating	80000	80000	80000
P(KW)load demand	51643.22923	27838.82181	59025.41825
Power Factor of load	0.645540365	0.347985273	0.737817728
I(rms)A	111.2964374	111.2964374	111.2964374
Z load	2.1528125	2.1528125	2.1528125
R (Ohm)load	1.389727368	0.749147045	1.588383228
X load	1.644159209	2.018261719	1.453148438
L (H) load	0.005233521	0.006424327	0.004625515

5.3.4 MATLAB MODEL
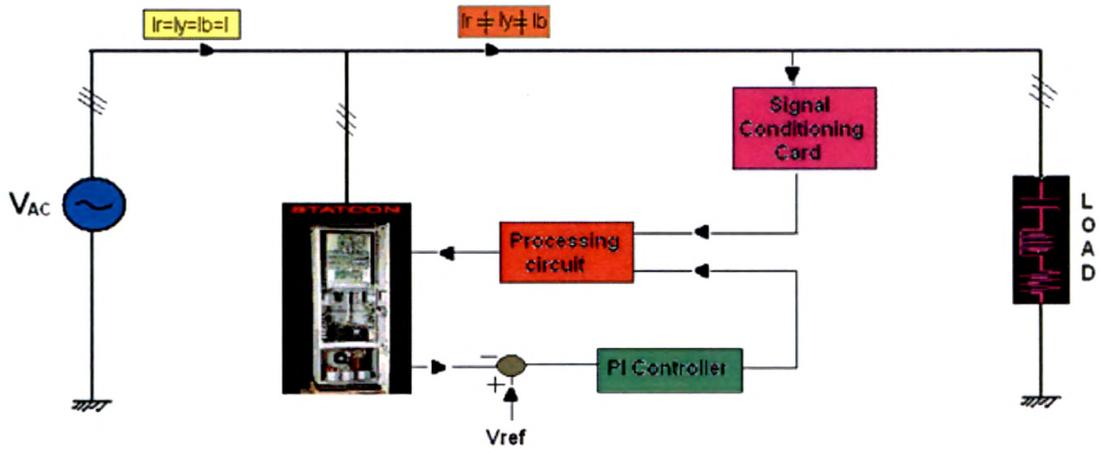
(a) Basic simulation scheme

Fig. 5.3 contd..
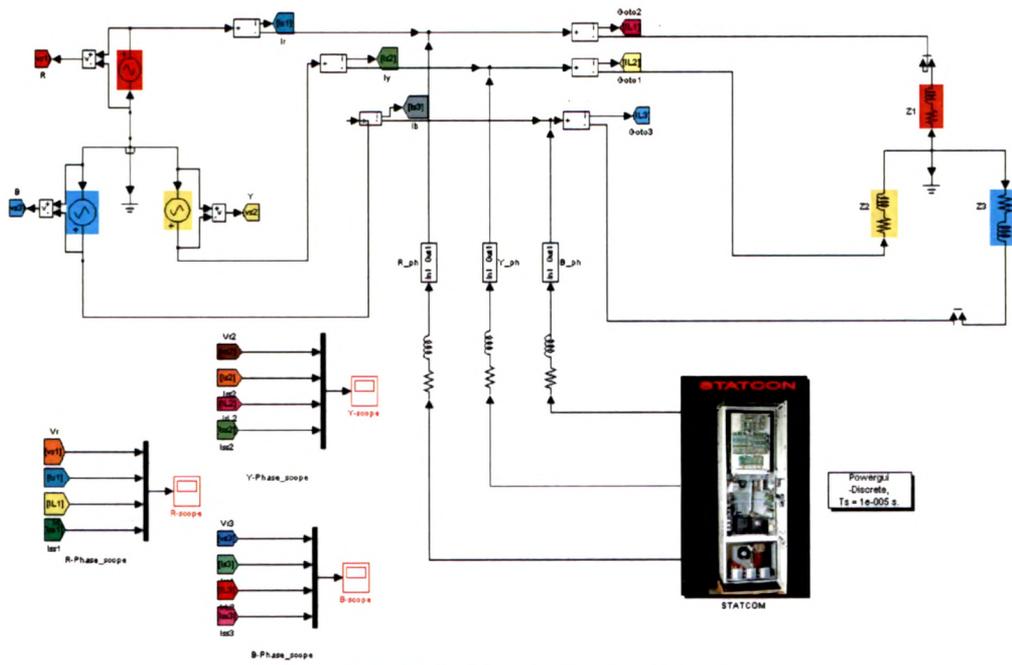
THREE PHASE REACTIVE POWER COMPENSATION
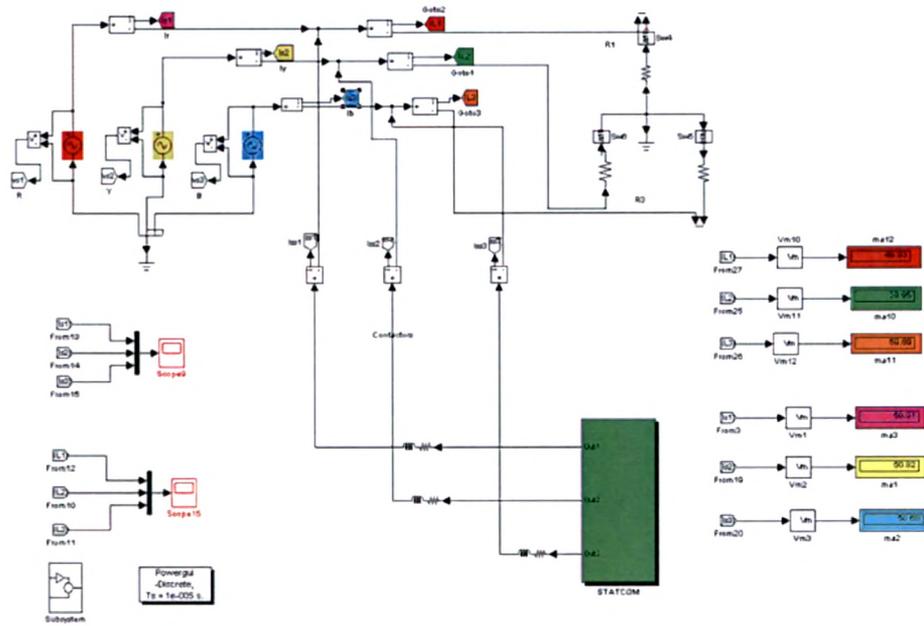
(b) MATLAB Model

Fig. 5.3 MATLAB Simulation model of STATCON with Load kW balancing

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SUBSYSTEM OF STATCON

Fig. 5.4 STATCON block as subsystem

5.3.5 SIMULATION RESULTS

Fig. 5.5 Triangular waveform is compared with sinusoidal waveform


Fig. 5.6 Converter voltage
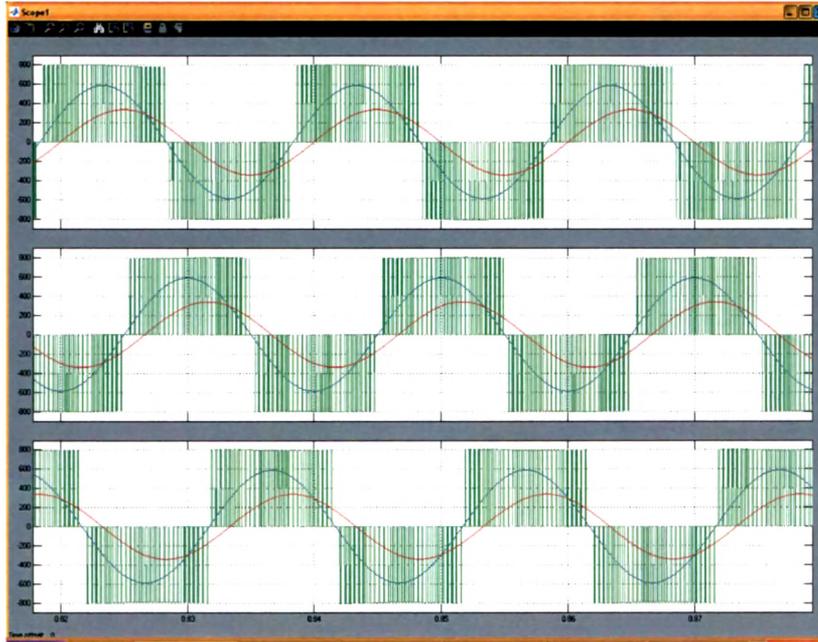
Fig. 5.7 waveforms for supply voltage phase and line, Statcon output voltage

Fig. 5.8 Voltage across DC bus capacitor

Fig. 5.9(a) below gives the STATCON connection for a three-phase load. The source voltage is considered as 415 V (L-L) and the load active currents delivered are 40A, 50A, and 60A

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(unbalanced operation). In fig. 5.9(b), the current waveforms are given for load as well as source currents after balancing is done.
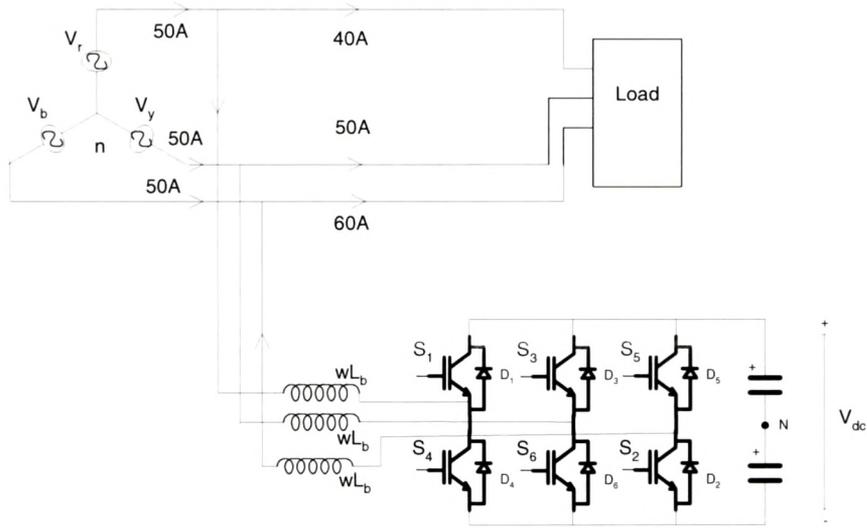
(a) STATCON connection for three-phase load
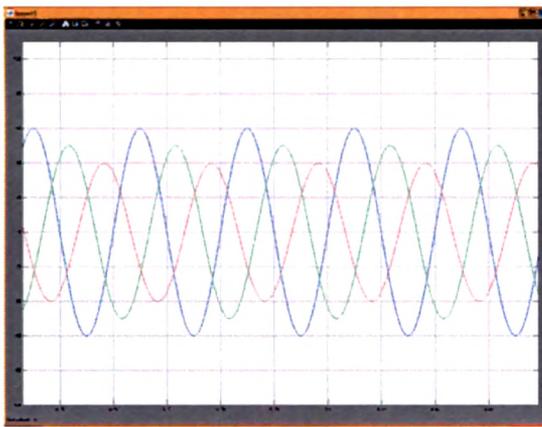
Wave forms of load current
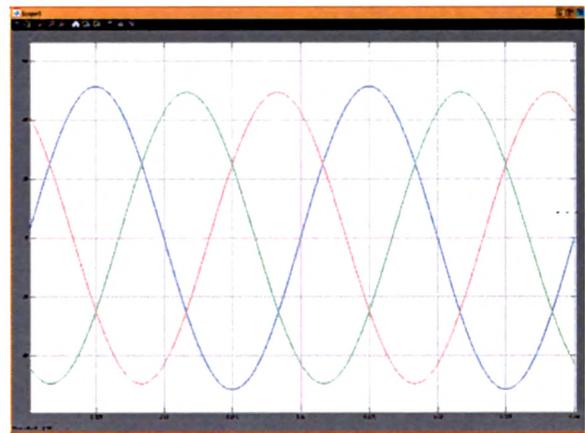
Waveforms of source current
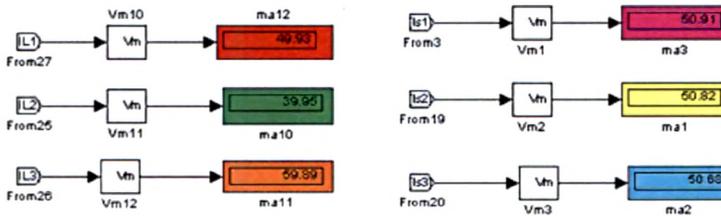
(b) Unbalanced Load currents and balanced source currents

Fig. 5.9 STATCON three-phase connection and load currents

Further, the same source is assumed to be supplying power to a three-phase load with unbalanced active current drain, with STATCON of approximately 60 kVAR capacity connected in shunt. Three cases are considered now as below.

Case 1: Load power 51 kW, pf = 0.6455 (STATCON supplying capacitive power equal load demanded inductive reactive power)

Case 2: Load power 59 kW, pf = 0.7378 (STATCON supplying capacitive power equal load demanded inductive reactive power and still having surplus capacity)

Case 3: Load power 27.8 kW, pf = 0.348 (STATCON supplying capacitive power within its capacity, but less than load demanded inductive reactive power)

The results of these three cases are given below now. It is to be noted that sign of the STATCON current shown is to be considered as negative (so that STATCON current shown below will appear capacitive). In case 1 and 2, the source current finally becomes in phase with incoming voltage. In case 3, it is still lagging as STATCON compensation is less than required by the load.
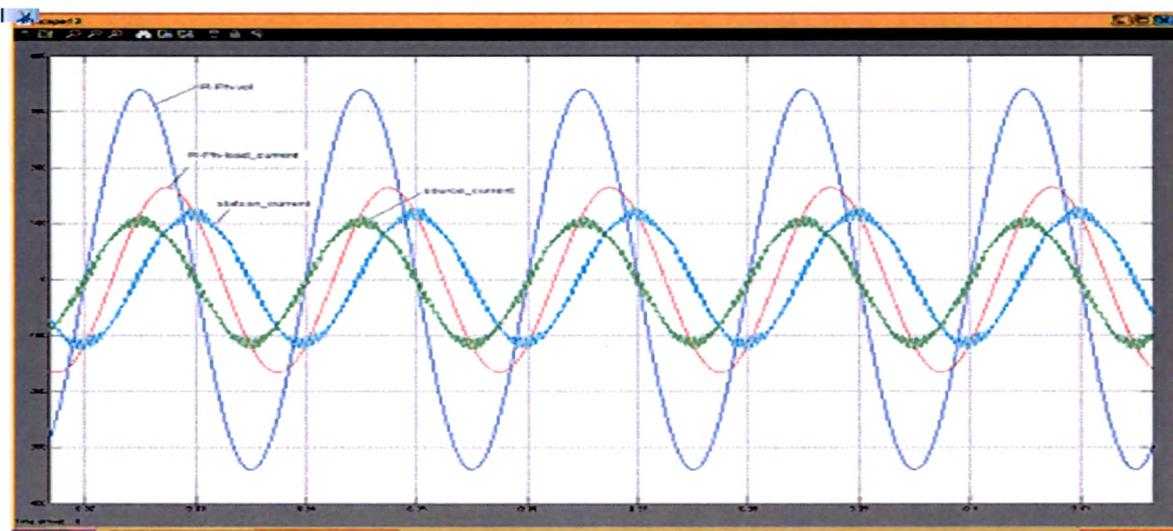

Fig.5.10 Voltage and Current waveforms as per Case 1
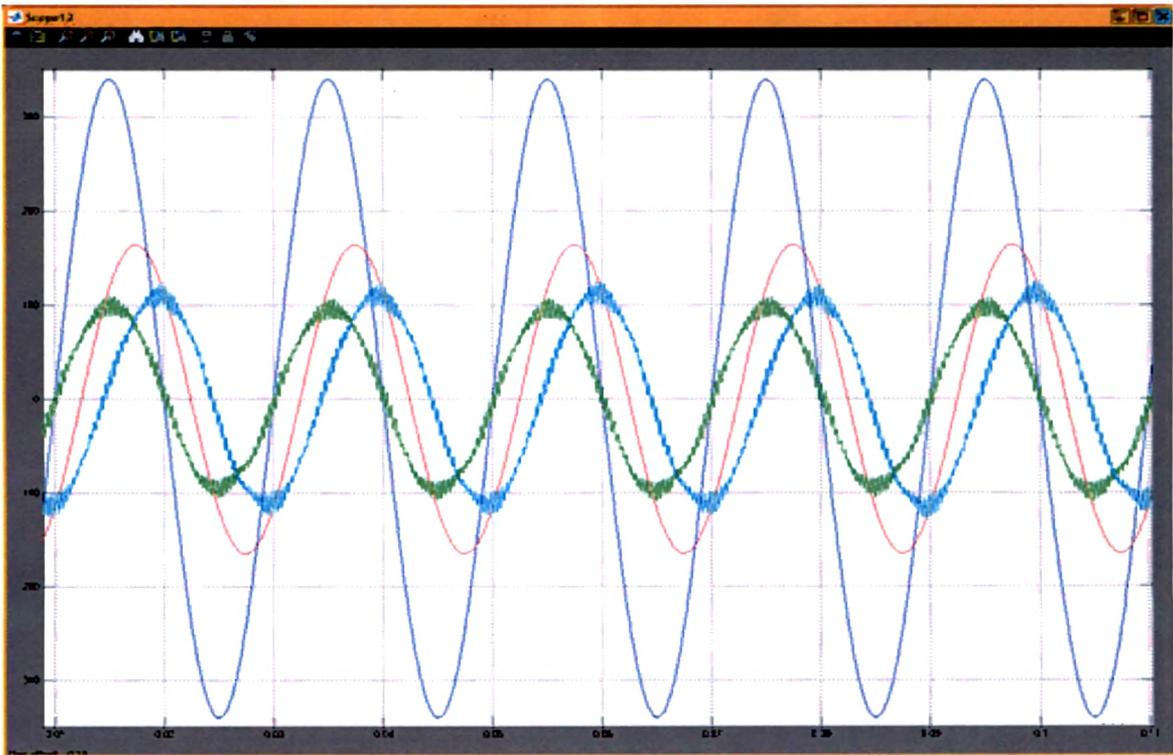
**Fig.5.11 Voltage and Current waveforms as per Case 2**
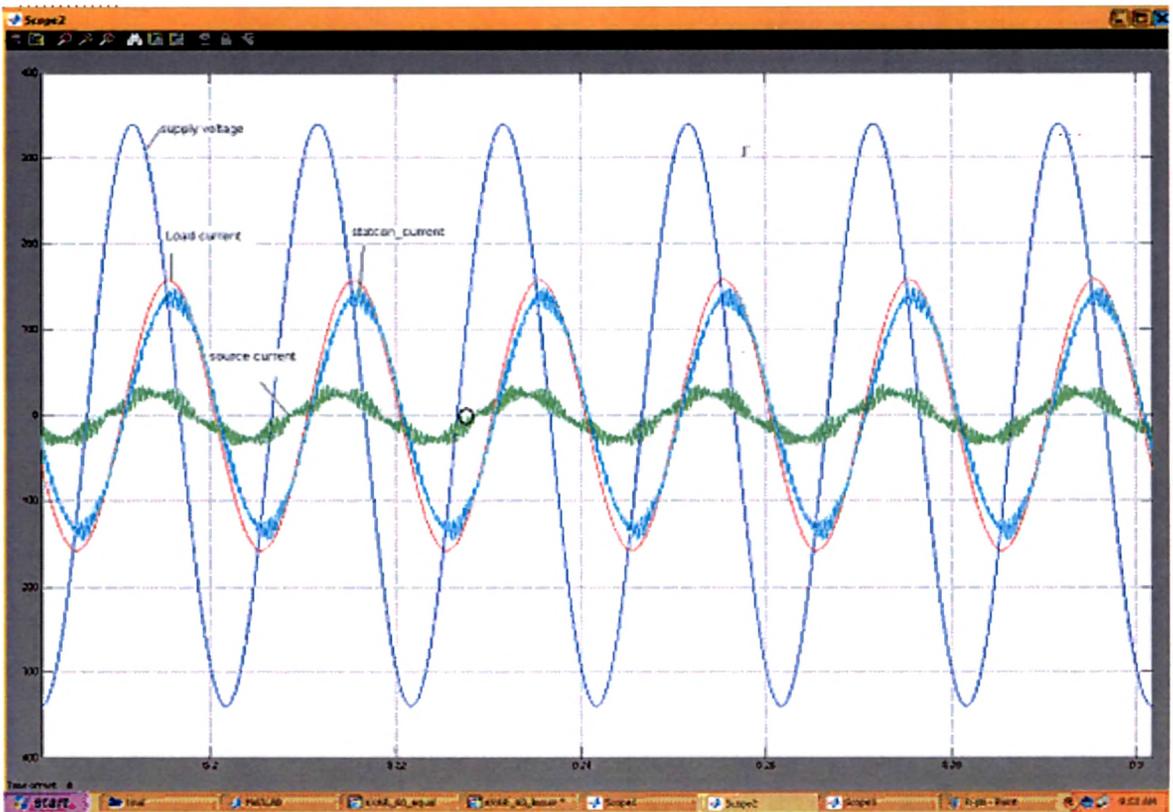
Fig.5.12 Voltage and Current waveforms as per Case 3

5.3.6 SUMMARY

The STATCON design for 60kVAR is simulated. The results depicted in earlier section justify the proposed concept for the reactive power compensation with Active Power Balance. The STATCON with a novel control concept achieves the Reactive Power Compensation along with Active Power balance provided the system in Unbalance condition see the sum of the load currents at any node should be zero.

In this implementation challenges have been faced for the implementation of PI controller to achieve the active power balance. By optimizing the PI parameter required performances were achieved.

Further, from simulation results in the present form, it is observed that STATCON having lower rating then the reactive power requirement of the system fails to compensate as expected. Where as, the STATCON having equal or higher rating is able to compensate. It is also observed, PI control implementation in present form, can balance maximum of 10A of active component by maintaining DC bus constant else, separate source needs to be supported to ensure DC bus is maintained in stable state/ within acceptable limits.

This in other view can also be looked as, that given converter rating can be shared as combination of maximum allowable reactive compensation and minimum allowable active power balance and if these limits are integrated in simulation, then active power balance restrictions can be further opened up on higher side. Extended details are covered in [227-229].

5.4 CONCLUSION

As presented, a basic STATCON can also be used for active power balancing. Most important is the calculation of fundamental components of the switching voltage of the converter. The Error "E", which decides proper operation of the dc voltage loop, needs to be calculated correctly for each phase. As stated earlier, the sizing of dc capacitors to absorb the second harmonic will have to be taken care of correctly. A separate calculation needs to be done to evaluate the second harmonic current under worst case of operation so as to transform the concept in practical product solution. Such load balancing is helpful in many applications, especially the Distribution Transformers (DTs) in LV networks.