ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

Three Level Cascaded STATCOM for Controlling Unbalanced Loads Using Sequence Components

Dr. D V VV CH Mouli[1], Suraj Kumar Singh[2]

Assistant Professor, Dept. of EEE, Hindustan University, Chennai, Tamilnadu, India[1]

PG Student [PSE], Dept. of EEE, Hindustan University, Chennai, Tamilnadu, India[2]

ABSTRACT: Multilevel inverters are used to increase the voltage level with less harmonics. This advantage can be utilized in designing STATCOM connected to the grid. High load applications used large amount of lagging loads, STATCOM should be capable to use as the VAR compensation in wide range for reactive load compensation. The dc-link voltages of the inverters are regulated at different levels to obtain multi-level operation. Multilevel inverter to be designed such that it produces higher voltage to fulfil the wide range of compensation simultaneously it should suppress the harmonics. So, in this paper necessary analysis and simulation to be observed to meet the above criterion. The simulation study is carried out in MATLAB/SIMULINK to predict the performance of the proposed scheme under balanced and unbalanced supply-voltage conditions with proposed unbalanced control.

KEYWORDS: Multi-level inverter, STATCOM, Total Harmonic Distortion (THD),Power Quality, Reactive Power Compensation, Voltage Source Converter (VSC),phase sequence, VAR compensation.

I.INTRODUCTION

In this paper the three level multi-level inverter is proposed. It is increasing the voltage level with less harmonics. It can also meet the wide range of reactive power compensation based firing angle control.

Normally 3-phase inverter produces 6n±1 level of harmonics. The harmonics[1] are further decreased if high number of pulses are used. Higher pulses required high switching frequency with switching losses. So, the multi-level inverter of 3-phase reduces the THD by increasing the number of levels. In multilevel inverter each level add with first level in certain percentage manner with some phase delay. The multi-level STATCOM uses the DC source for single level with using capacitors in other levels or using dc sources in all levels of the STATCOM . In the proposed system 3-level VSI is used for STATCOM. With this 3-level inverter by connecting to the unbalanced system, suitable controlling method using phase sequence components is also proposed. Different outputs are observed at different points for better analysis. Finally the stability of sensitivity function is also analysed. The STATCOM is proposed with new generation type using voltage source inverter. The multilevel inverter also quickly damp out the transient oscillations. So the multilevel inverter reduces the switching complications in complicated grid networks.

In this paper, the compensation using cascaded 3-level STATCOM is used with asymmetrical control with unbalanced condition.

II.CASDADED MULTILEVEL INVERTER

Cascaded multilevel inverter[2] is used either in capacitor mode or inductive mode. Real and reactive power flow of each level may be differed with total 3-level together. It may work as converter as well as inverter. The high level application usage depends up on maintenance cost and harmonic distortion, high power application. Different structures like H-bridge[3,4] ,flying capacitor mode are used for the multilevel inverter. The number of levels at the output is depend on switching sequence of each level.

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

III. CASCADED THREE-LEVEL INVERTER-BASED MULTILEVEL STATCOM

Fig. 1 shows the three level cascaded multilevel inverter connected to the system with unbalanced loads. The unbalanced loads are resistive and inductive type. The inverters of the STATCOM are connected on the high-voltage (HV) side of the transformer with 2:1 ratio, and the low voltage (LV) side is connected to the power system. The dc-link voltages of the inverters are maintained constant and modulation indices are controlled to achieve the required objective. The THD at one phase of multi-level output is 3.17%.

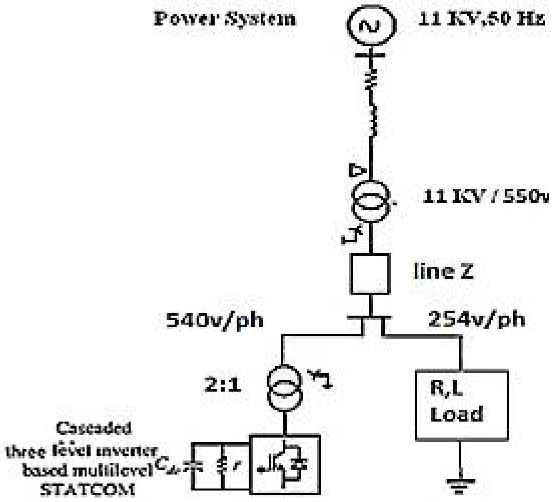

Fig. 1 : Cascaded level connected to the system.

Fig 2. shows the Matlab circuit topology of the cascaded three level inverter based multilevel STATCOM .

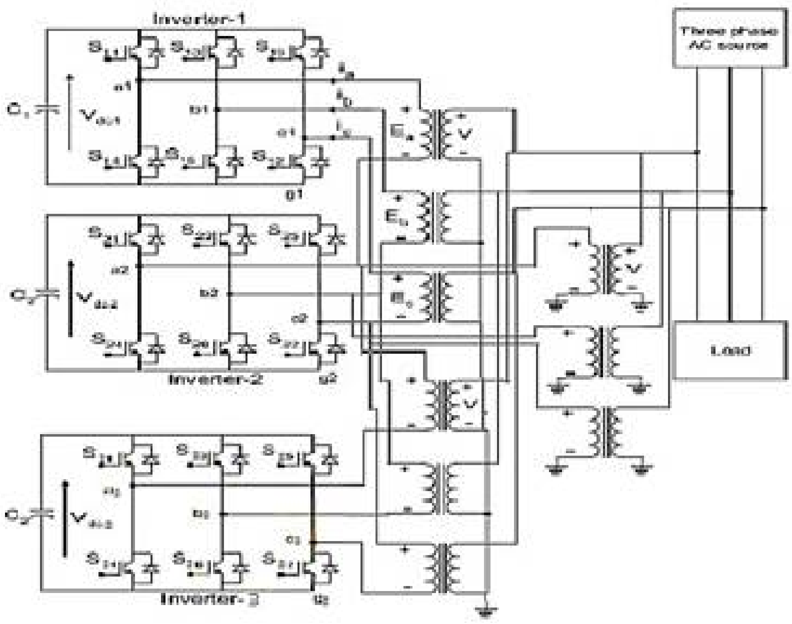

Fig. 2: Matlab circuit for 3 level inverter STATCOM

Fig 2a. shows the equivalent block diagram of 3-level STATCOM

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

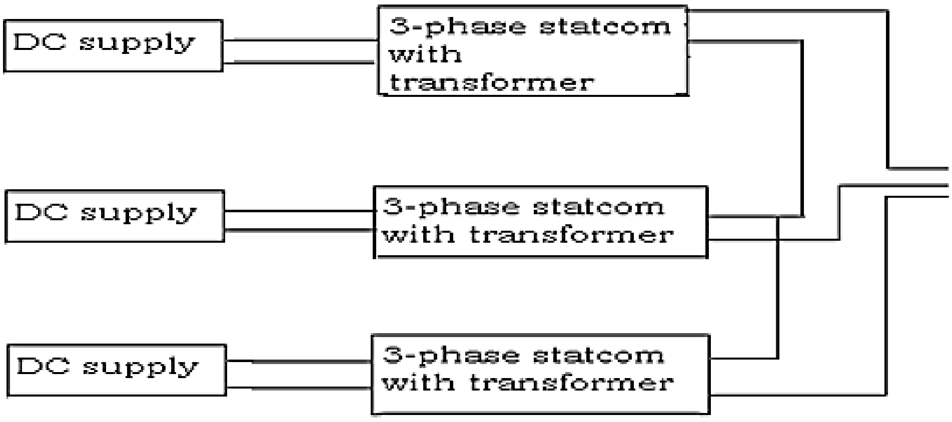

Fig. 2a: Equivalent block diagram of 3-level STATCOM

$$Ri_a + Ldi_a/dt = V_a - [e_{a1} + e_{a2} + e_{a3}]$$
$$Ri_b + L\, di_b/dt = V_b - [e_{b1} + e_{b2} + e_{b3}]$$
$$Ri_c + L\, di_c/dt = V_c - [e_{c1} + e_{c2} + e_{c3}] \quad (1)$$

In fig 3,4 the multilevel output observed in each phase from matlab simulation are shown.

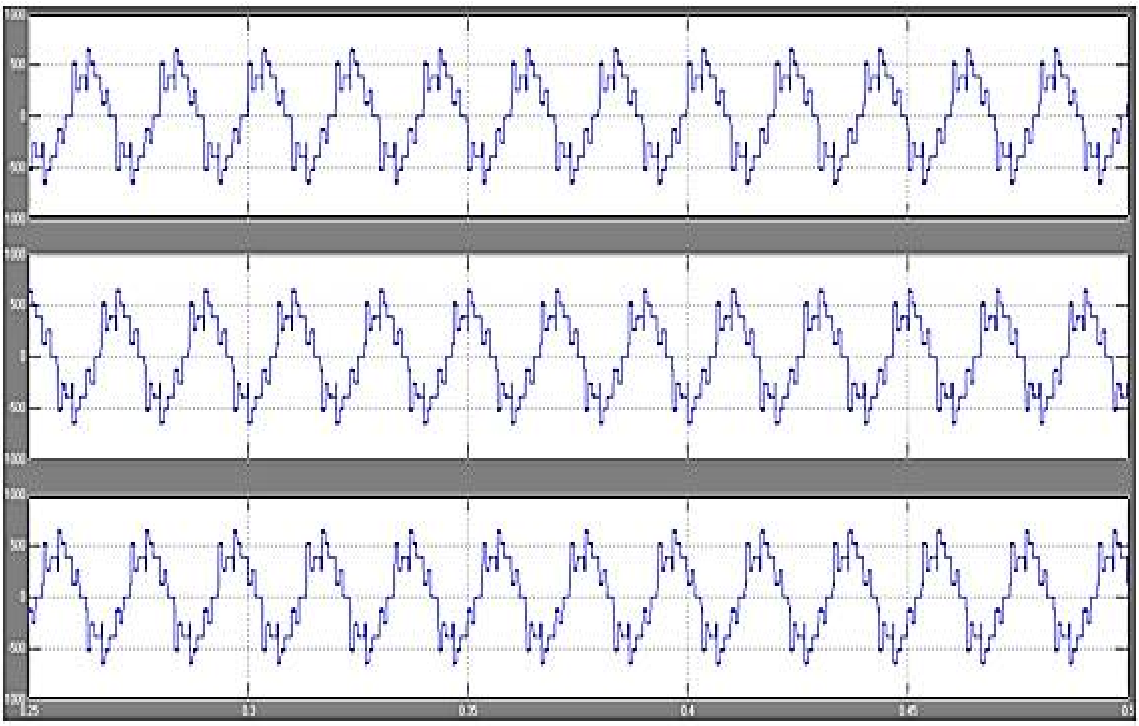

Fig. 3: multilevel voltage output at each phase

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

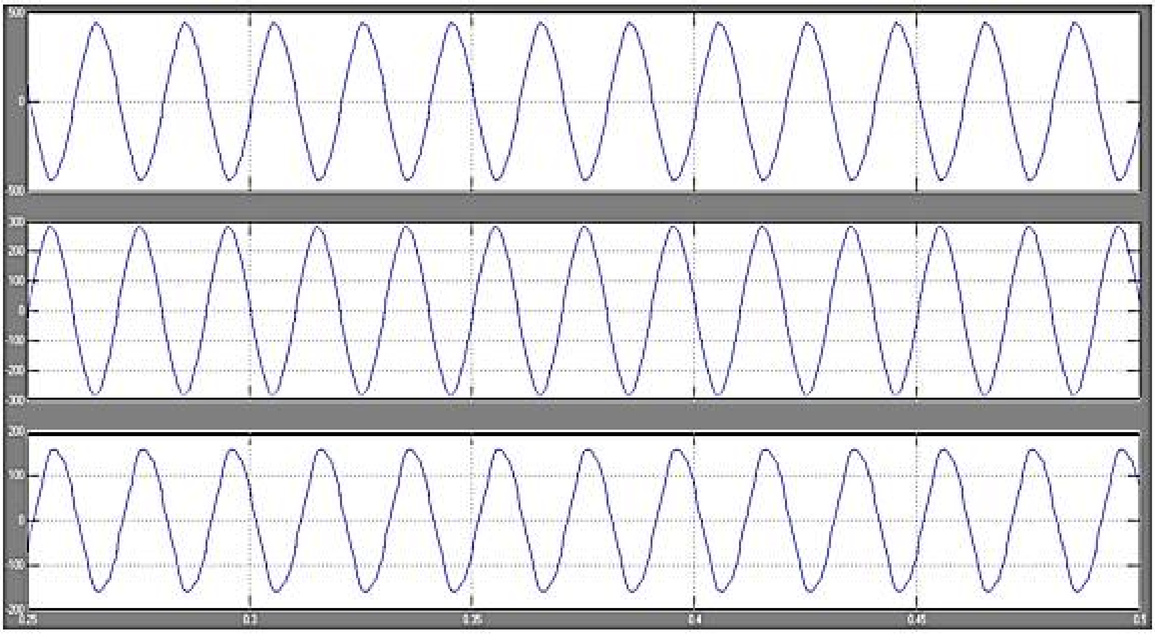

Fig. 4: System voltage output in each phase.

CONTROL OF REACTIVE POWER

The reactive power and real power both can be controlled using the 3-levelstatcom. The reactive power flow depends on voltage differences between statcom and system[5]. The real power flow depends up on angle between the statcom voltage and the system voltage. The STATCOM output voltage is controlled by modulating index provided with each inverter modulating index is within the linear range.

IV. UNBALANCED SYSTEM

The fig.5. shows the matlabsimulink model of multilevel inverter connected to the unbalanced system. The details of the multilevel inverter, grid generation and load details are given below.

Details of Multilevel inverter

DC value = 500V R=1Ω C= 1uf

Details of System Parameters

Ph-Ph RMS value = 550V, f=50H_z

Details of Load Details

A-phase P = 10KW Q= 10 var(inductive)
B-Phase P = 200KW Q=100 var(inductive)
C-Phase P = 300KW Q= 1000 var(inductive)

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

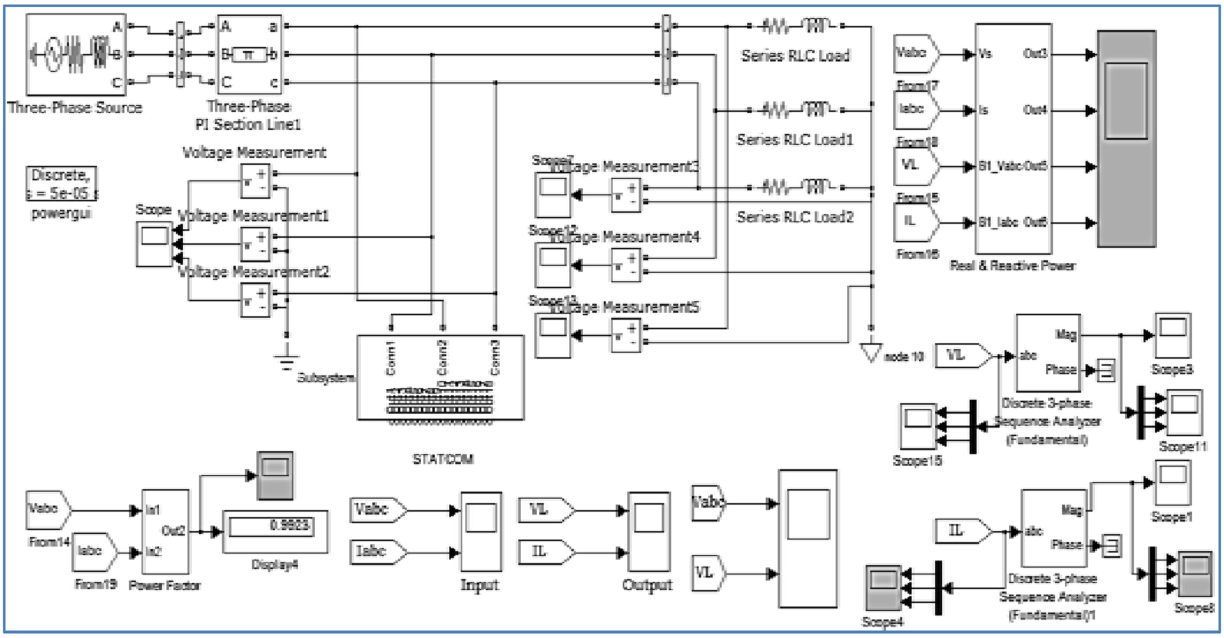

Fig.5: Simulink model of transmission system with STATCOM

The table 1 shows the different sequence parameters comparison observed by connecting the STATCOM to the system using MATLAB. These sequence parameters are used for controlling the STATCOM under unbalanced condition. The unbalanced loads are causing excessive heating of the machines due to voltage fluctuations. These voltage fluctuations are controlled by STATCOM control using Sequence components. Considerable sequence components are generated for more variation of loads in each phase which leads to more unbalance. Sequence parameters are also more by connecting STATCOM to the system.

Table 1: comparison of system sequence parameters with and without STATCOM

Parameters of system without STATCOM at 50hz	**Parameters of system with STATCOM at 50hz**
• **Sequence voltage** V_L^+ = 225V V_L^- = 185V V_L^0 = 0V	• **Sequence voltage** V_L^+ = 240V V_L^- = 195V V_L^0 = 0V
• **Sequence current** I_L^+ = 9.5A I_L^- = 6.4A I_L^0 = 0A	• **Sequence current** I_L^+ = 11.8A I_L^- = 8.2A I_L^0 = 0A
• **Voltage across load (peak values)** V_{ab} = 410V V_{bc} = 250V V_{ca} = 150V	• **Voltage across load (peak values)** V_{ab} = 440V V_{bc} = 290V V_{ca} = 160V
• **Power factor** = 0.9822	• **Power factor** = 0.9924
• **Current across line** I_a = 5.9A I_b = 15.5A I_c = 11A	• **Current across line** I_a = 7A I_b = 19A I_c = 14A

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

SIMULATION RESULT

SEQUENCE VOLTAGE :Fig 6 shows the observed sequence voltages using matlab.A very small zero sequence voltage is developing across the load. The zero sequence amplitude is showing most random nature in both without and with STATCOM. The magnitude of positive and negative sequence voltage is increased by connecting STATCOM to the system. This is happening for sequence currents also as shown in fig.7.

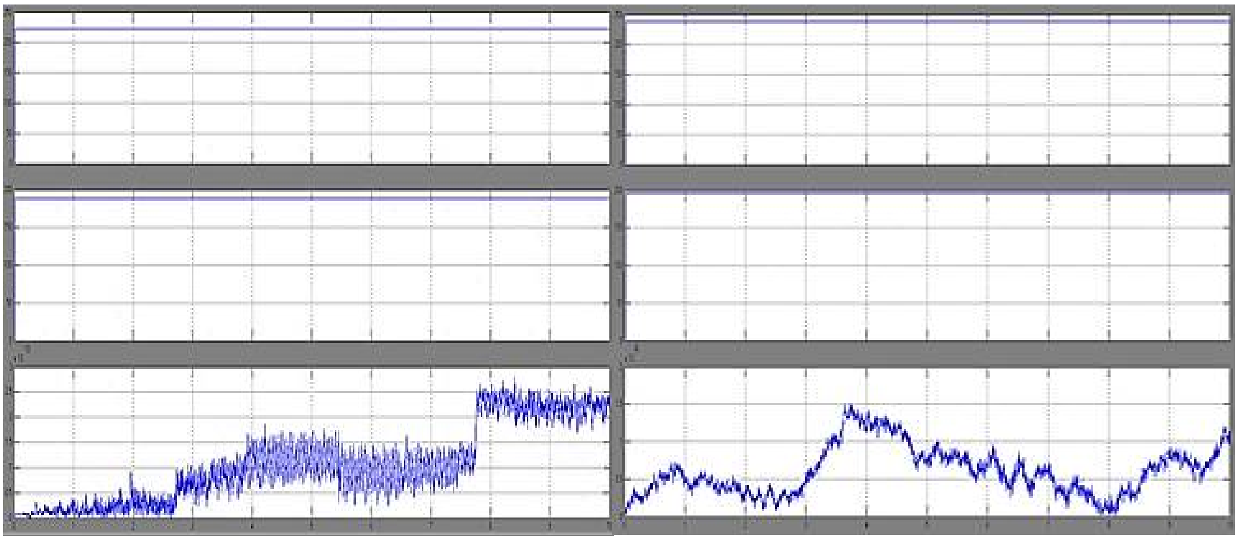

Fig. 6a Fig. 6b

Fig. 6: Sequence voltages of the system without and with STATCOM

SEQUENCE CURRENTS :

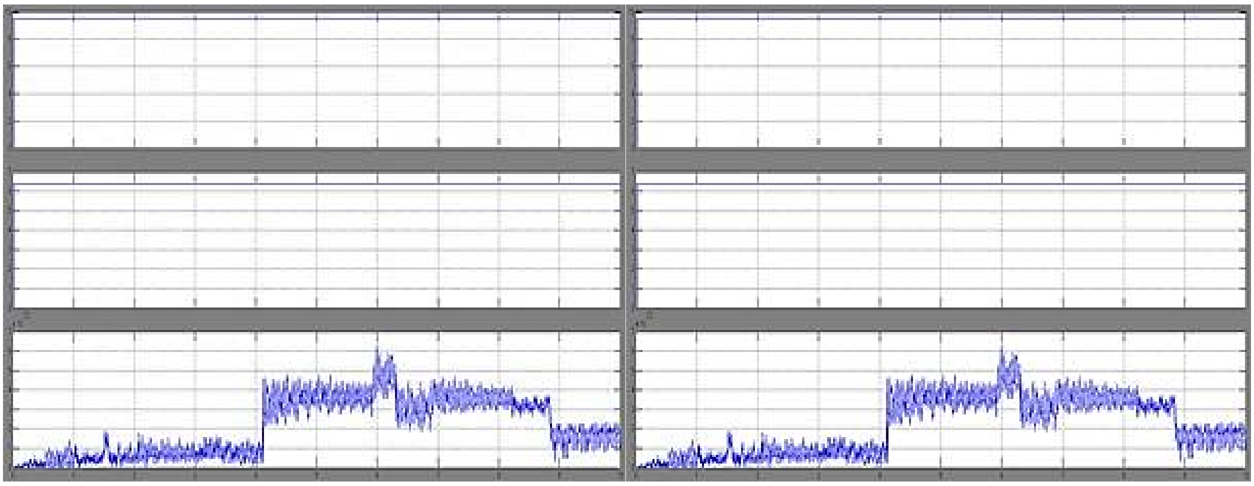

Fig. 7a Fig. 7b

Fig. 7: Sequence currents of the system without and with STATCOM

POWER FACTOR :- The power factor increased when STATCOM is connected to the system. The raising of the power factor is showing little bit time delay after connecting the STATCOM as shown in fig 8.b. the time delay is due to STATCOM controlling delay.

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

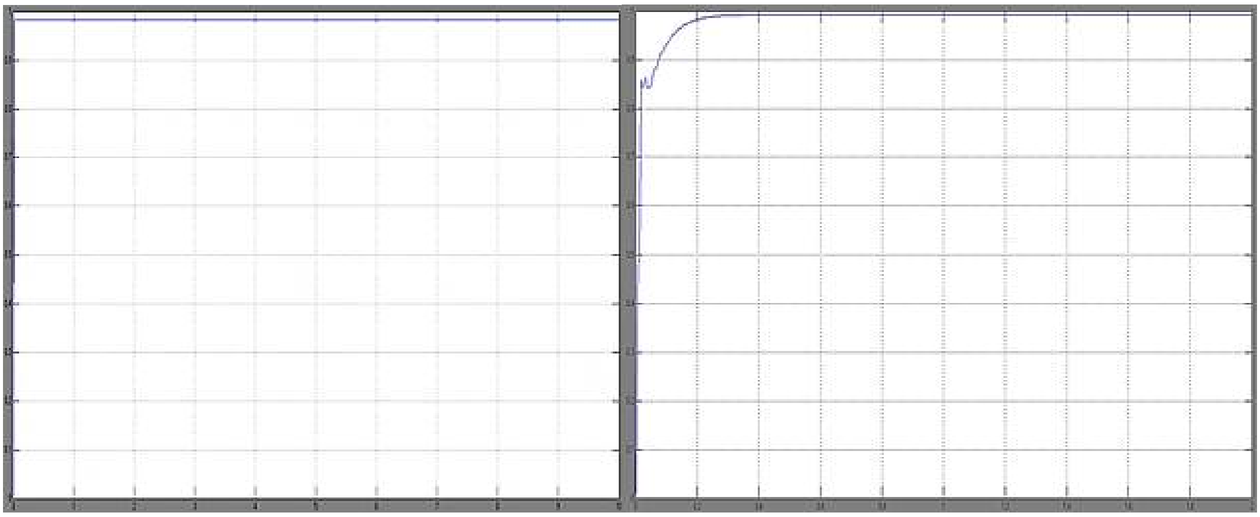

Fig. 8a Fig. 8b

Fig. 8: Power factor of the load without and with STATCOM

VOLTAGE AND CURRENT ACROSS LOAD (PEAK VALUES):-The load voltages and currents are showing high peak value by connecting STATCOM to the system with THD of load current is 3.65%

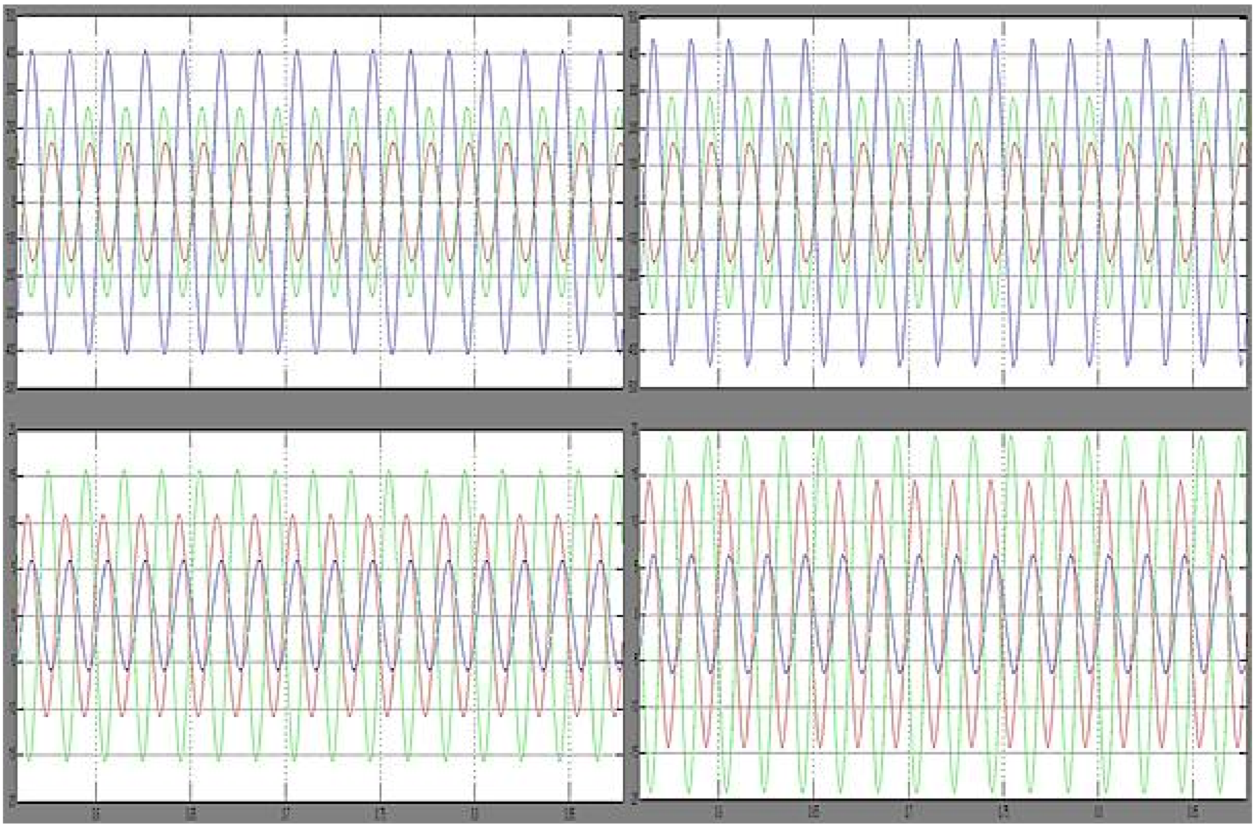

Fig. 9a Fig. 9b

Fig. 9 : Load voltages and currents without and with STATCOM

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

CURRENT ACROSS LINE:

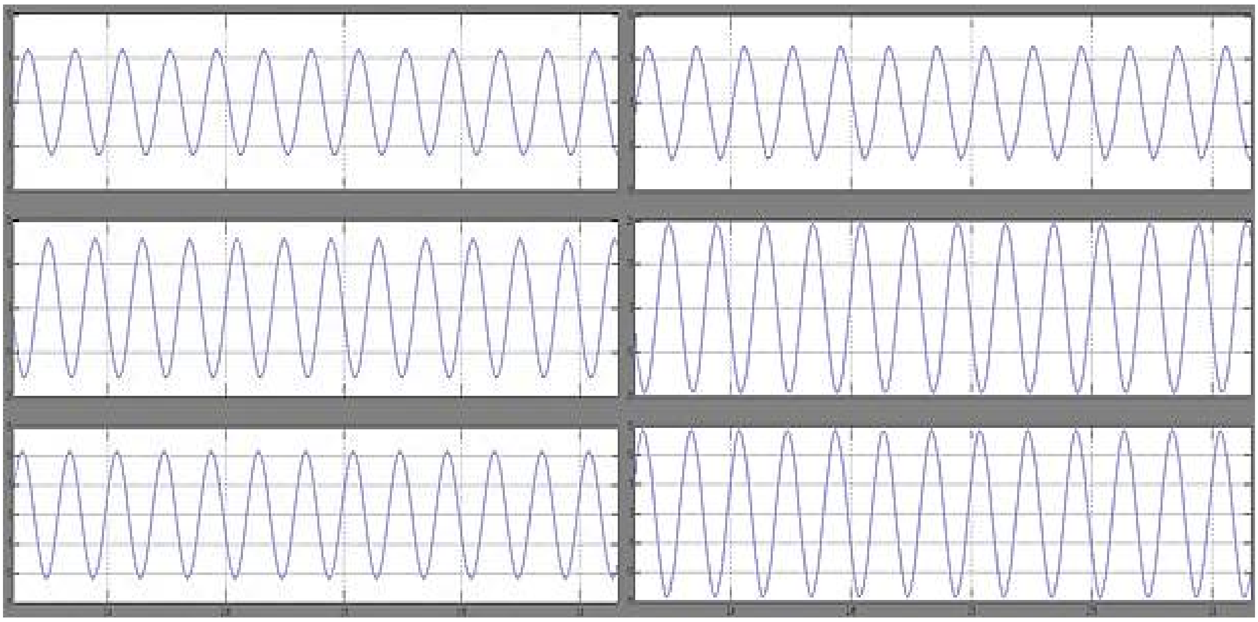

Fig. 10a Fig. 10b

Fig. 10 : current across the line without and with STATCOM

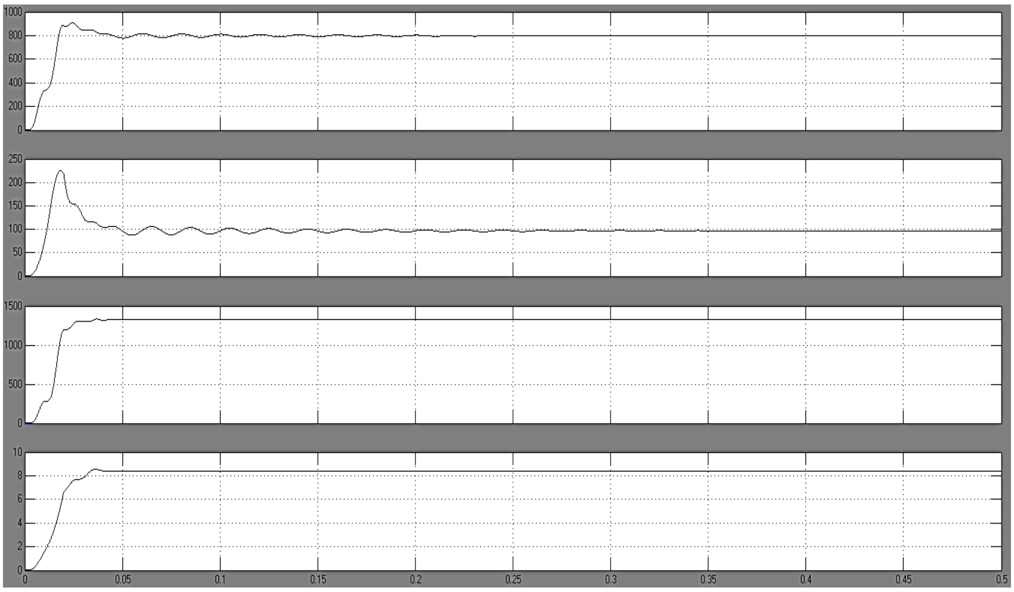

Fig.11 Real and Reactive power at source and load side with STATCOM

In above Fig 11. the source reactive power is showing overshoot with some settling time whereas load side only rise time is shown.

Comparison of DC currents without and with connecting of STATCOM to the system:

The capacitor currents are showing charging and discharging pulses in both cases. The fig.12 is showing capacitive current without and with connecting the STATCOM at 1st level of the inverter. Fig.13 is showing STATCOM input current at 1st level of the inverter. Similarly fig14 and fig.15 are showing for second level and Fig.16 and Fig.17 are showing for 3rd level of the three level inverter

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

STATCOM without connecting to the system **STATCOM connecting to the system**

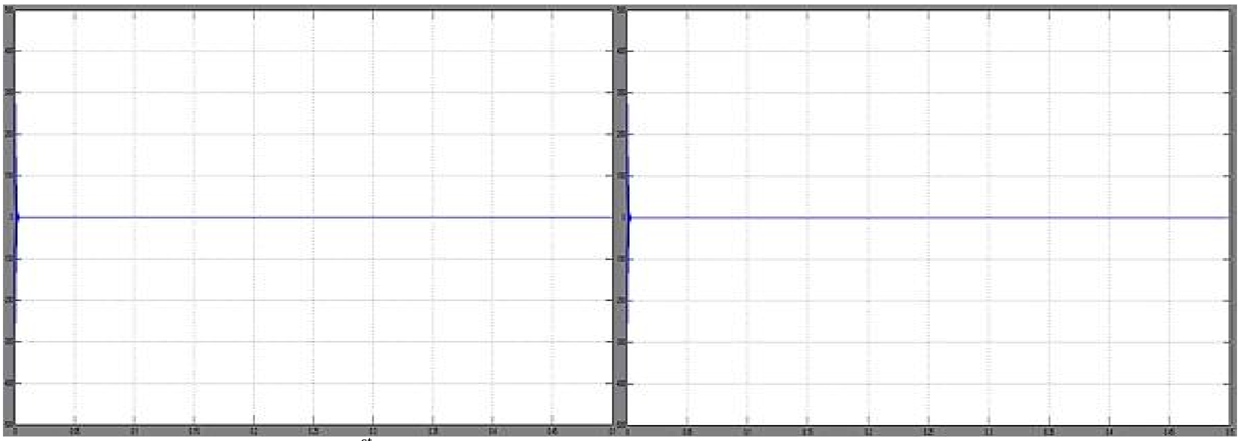

Fig. 12 1st LEVEL STATCOM INPUT CAPACITOR CURRENT

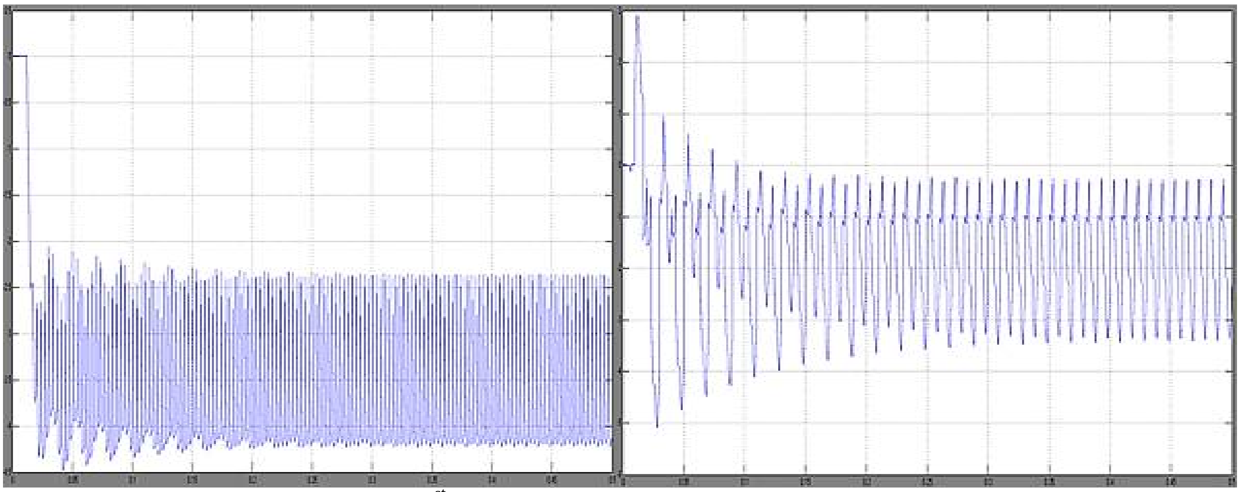

Fig. 13 1st LEVEL STATCOM INPUT CURRENT

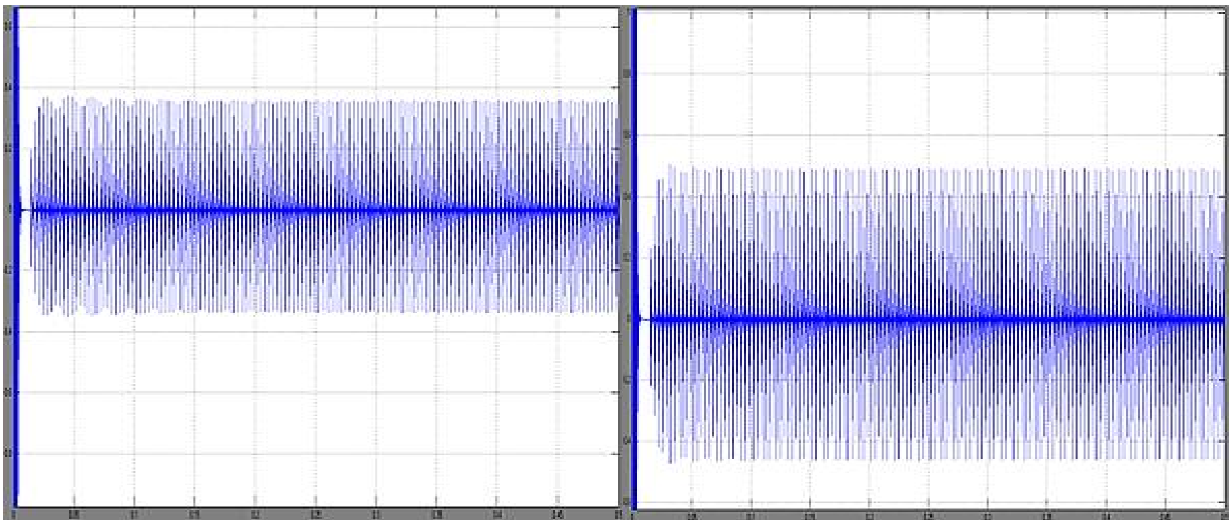

Fig. 14 2nd LEVEL STATCOM INPUT CAPACITOR CURRENT

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

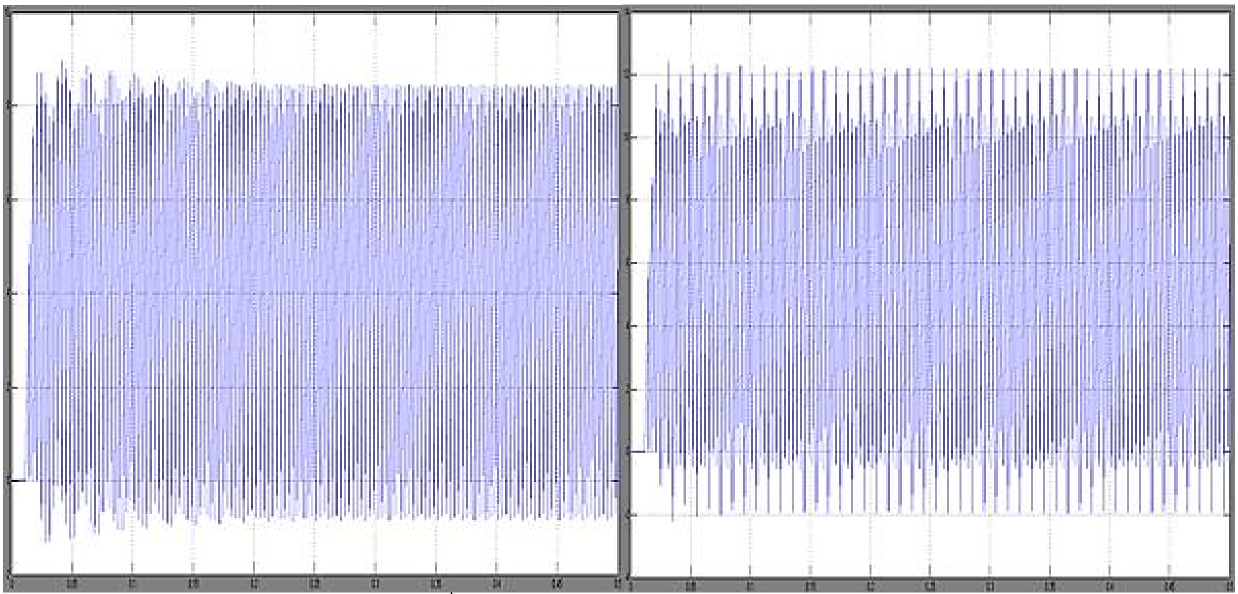

Fig. 15 2nd LEVEL STATCOM INPUT CURRENT

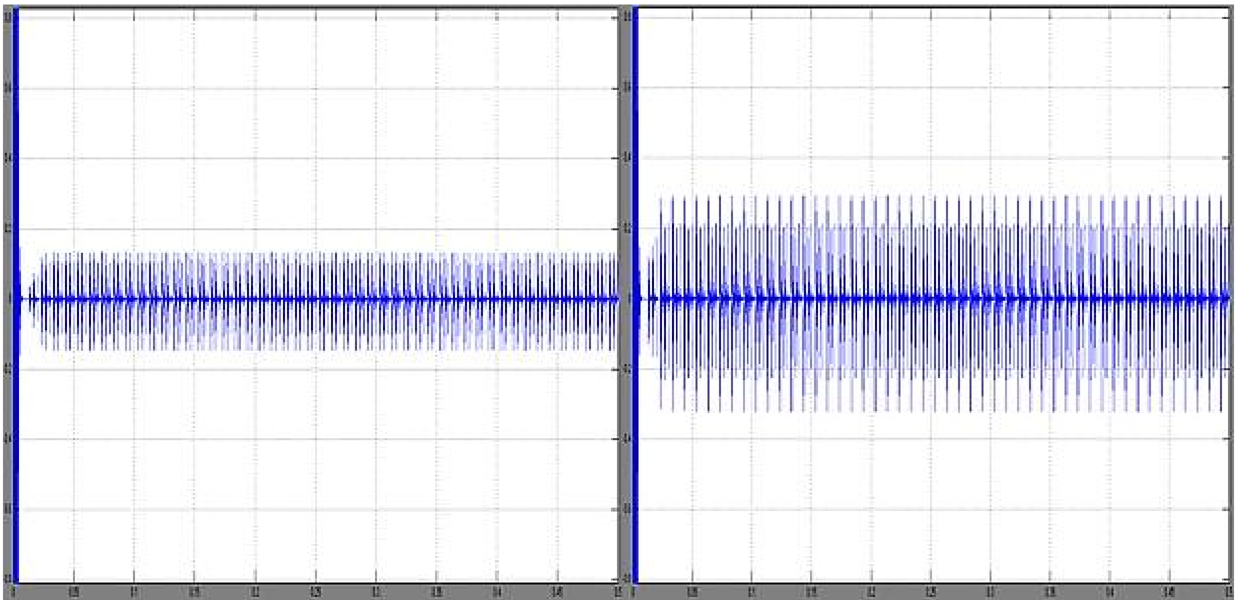

Fig. 16 3rd LEVEL STATCOM INPUT CAPACITOR CURRENT

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

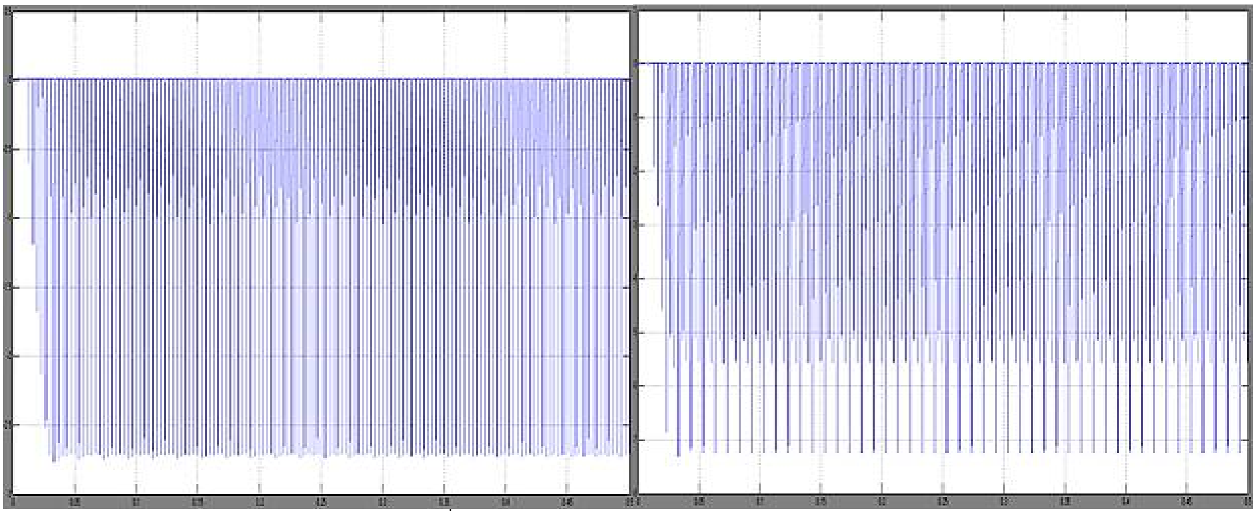

Fig. 17 3rd LEVEL STATCOM INPUT CURRENT

- In all the above simulation output figures the X –axis is time scale in seconds, Y- axis is in corresponding parameters with its units.

PHASE SEQUENCE CONVERSION:

The symmetrical components can be used to determine any unbalanced current or voltage (I_a, I_b, I_c or V_a, V_b, V_c) as follows:

CURRENT

$I_a = I_{a1} + I_{a2} + I_{a0}$
$Ib = a^2 I_{a1} + aI_{a2} + I_{a0}$
$Ic = aI_{a1} + a^2 I_{a2} + I_{a0}$

I_{abc} = (7.0000 -89.9420
19.0000 -209.9710
14.0000 -328.0970)

VOLTAGE

$Va = V_{a1} + V_{a2} + V_{a0}$
$Vb = a^2 V_{a1} + aV_{a2} + V_{a0}$
$Vc = aV_{a1} + a^2 V_{a2} + V_{a0}$

V_{abc} = (620 0
95 -120
48 -240)

The sequence currents or voltages from a three-phase unbalanced set with STATCOM can be calculated using the following equations:

Zero Sequence Component:

$I_{a0} = ⅓ (I_a + I_b + I_c)$
$I_{a0} = 3.6313 \angle 114.7855$

$V_{a0} = ⅓ (V_a + V_b + V_c)$
$V_{a0} = 183.3361 \angle -4.2440$

Positive Sequence Component:

$I_{a1} = ⅓ (I_a + aI_b + a^2 I_c)$
$I_{a1} = 13.3317 \angle -89.3100$

$V_{a1} = ⅓ (V_a + aV_b + a^2 V_c)$
$V_{a1} = 254.3333 \angle 0.0000$

Negative Sequence Component:

$I_{a2} = ⅓ (I_a + a^2 I_b + aI_c)$
$I_{a2} = 3.3285 \angle 65.7157$

$V_{a2} = ⅓ (V_a + a^2 V_b + aV_c)$
$V_{a2} = 183.3361 \angle 4.2440$

Similarly

$I_{b1} = 13.3317\angle 150.69$ $\quad V_{b1} = 254.3333\angle 240$

$I_{b2} = 3.3285\angle 185.7157$ $\quad V_{b2} = 183.3361\angle 124.2440$

$I_{c1} = 13.3317\angle 30.69$ $\quad V_{c1} = 254.3333\angle 120$

$I_{c2} = 3.3285\angle 305.7157$ $\quad V_{c2} = 183.3361\angle 244.2440$

Where $I_{a0}=I_{b0}=I_{c0}$ $\quad V_{a0}=V_{b0}=V_{c0}$

V. SEQUENCE CONTROLLING OF STATCOM

The Figure18. shows the firing angle control of the multi-level STATCOM using modulation index variation using simultaneous sequence voltage, dq voltage , αβ voltage sensing with proper time delay
The dq phase sequences are obtained from phase sequence voltages[6]. Whereas in balanced loads ,dq transformation is obtained from phase voltages. Compared to the zero sequence component, Negative sequence component gives the significant contribution for controlling STATCOM.

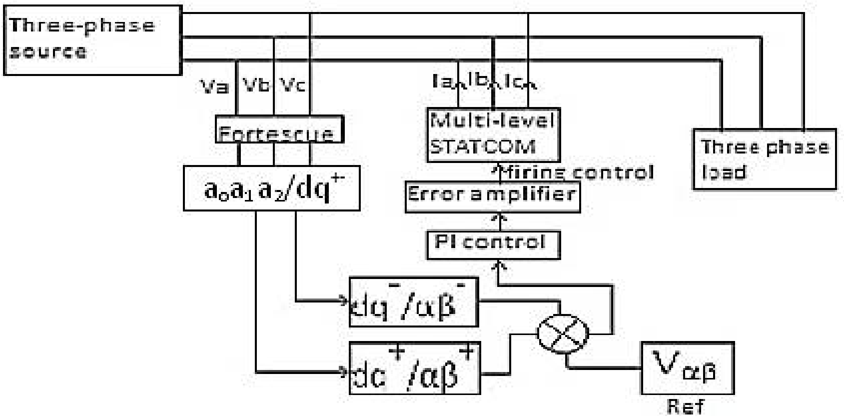

Fig. 18 Sequence controlling of the STATCOM

$$\begin{pmatrix} V_q^{+} \\ V_d^{+} \\ V_q^{-} \\ V_d^{-} \\ V_q^{0} \\ V_d^{0} \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 0 & -\frac{1}{6}-\frac{\sqrt3}{6} & -\frac{1}{6}-\frac{\sqrt3}{6} & 2\cos\theta & 0 & 0 \\ \frac{1}{3} & 0 & -\frac{\sqrt3}{6} & -\frac{1}{6}-\frac{\sqrt3}{6}-\frac{1}{6} & -2\sin\theta & 0 \\ \frac{1}{3} & 0 & -\frac{1}{6} & -\frac{\sqrt3}{6}-\frac{1}{6}-\frac{\sqrt3}{6} & 0 & 2\cos\theta \\ \frac{1}{3} & 0 & \frac{\sqrt3}{6} & -\frac{1}{6}-\frac{\sqrt3}{6}-\frac{1}{6} & 0 & -2\sin\theta \\ \frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{3} & 0 \\ 0 & \frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{3} \end{pmatrix} \begin{pmatrix} 0 & & & \\ 0 & 1 & 1 & 1 \\ 0 & & a^2 & a \\ 0 & a & a^2 & 1 \\ & 2\cos\theta & & \\ & -2\sin\theta & & \end{pmatrix} \begin{pmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{pmatrix}$$

$$\begin{pmatrix} V_q^{+} \\ V_d^{+} \\ V_q^{-} \\ V_d^{-} \\ V_q^{0} \\ V_d^{0} \end{pmatrix} = \begin{pmatrix} j\sin\theta+\cos\theta & -j\sin\theta+\cos\theta & 0 \\ -\frac{1}{2}\sin\theta+(\frac{2}{3}+j)\cos\theta & -\frac{1}{2}\sin\theta+(\frac{2}{3}-j)\cos\theta & \frac{2}{3}\sin\theta+\frac{2}{3}\cos\theta \\ -j\sin\theta+\cos\theta & j\sin\theta+\cos\theta & 0 \\ -\frac{1}{2}\sin\theta+(\frac{2}{3}+j)\cos\theta & -\frac{1}{2}\sin\theta-(\frac{2}{3}-j)\cos\theta & \frac{2}{3}\sin\theta+\frac{2}{3}\cos\theta \\ 0 & 0 & 2\cos\theta \\ 0 & 0 & -2\sin\theta \end{pmatrix} \begin{pmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{pmatrix}$$

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

$$V_{\alpha\beta\gamma} = [2/3]^{1.5} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & 1.732/2 & -1.732/2 \\ ½ & ½ & ½ \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 1.414/2 \\ \cos(\theta-120^0) & -\sin(\theta-120^0) & 1.414/2 \\ \cos(\theta+120^0) & -\sin(\theta+120^0) & 1.414/2 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix}$$

VI. REACTIVE POWER SENSITIVITY TRANSFER FUNCTION

$Si_q = -\omega[i_d] - \frac{r}{l} i_q + \frac{1}{L}[V_q - (e_{q1} + e_{q2} + e_{q3})]$

$Si_d = -\frac{r}{l} i_d + \omega[i_q] + \frac{1}{L}[V_d - (e_{d1} + e_{d2} + e_{d3})]$

$Si_q = -\omega[i_d] - \frac{r}{l} i_q + \frac{1}{L}[V_{q\sim}]$

$Si_d = -\frac{r}{l} i_d + \omega[i_q] + \frac{1}{L}[V_{d\sim}]$

$Si_d + \frac{r}{l} i_d = \omega[i_q] + \frac{1}{L}[V_{d\sim}]$

$(s + \frac{r}{l})\, i_d = \omega[i_q] + \frac{1}{L}[V_{d\sim}]$

$i_d = \frac{\omega}{(s+\frac{r}{l})} i_q + \frac{1}{L(s+\frac{r}{l})}[V_{d\sim}]$

$Si_q = -\omega\,[\frac{\omega}{(s+\frac{r}{L})} i_q + \frac{1}{L(s+\frac{r}{L})}(V_{d\sim})] - \frac{r}{L} i_q + \frac{1}{L}[V_{q\sim}]$

$Si_q = -\frac{\omega 2}{(s+\frac{r}{l})} i_q - \frac{r}{L} i_d - \frac{\omega}{L(s+\frac{r}{L})}[V_{d\sim}] + \frac{1}{L}[V_{q\sim}]$

if $V_{d\sim} = 0$

$Si_q + \frac{\omega 2}{(s+\frac{r}{l})} i_q + \frac{r}{L} i_q = \frac{1}{L}[V_{q\sim}]$

$T_{sen}\Big|_{vd\sim} = i_q / V_{q\sim} = \dfrac{\frac{1}{L}}{s + [\frac{\omega 2}{(s+\frac{r}{l})} + \frac{r}{L}]}$

$$= \frac{(s+\frac{r}{L})}{s(s+\frac{r}{L})L + \omega 2L + r(s+\frac{r}{L})} \quad (5)$$

For multilevel inverter , L=0.596h,ω=314rad/sec ,R=0.0149Ω

Bode plot and Root locus of sensitive function:- From the bode plot and root locus with all values of K, it is observed that the sensitivity function shows the stable response.

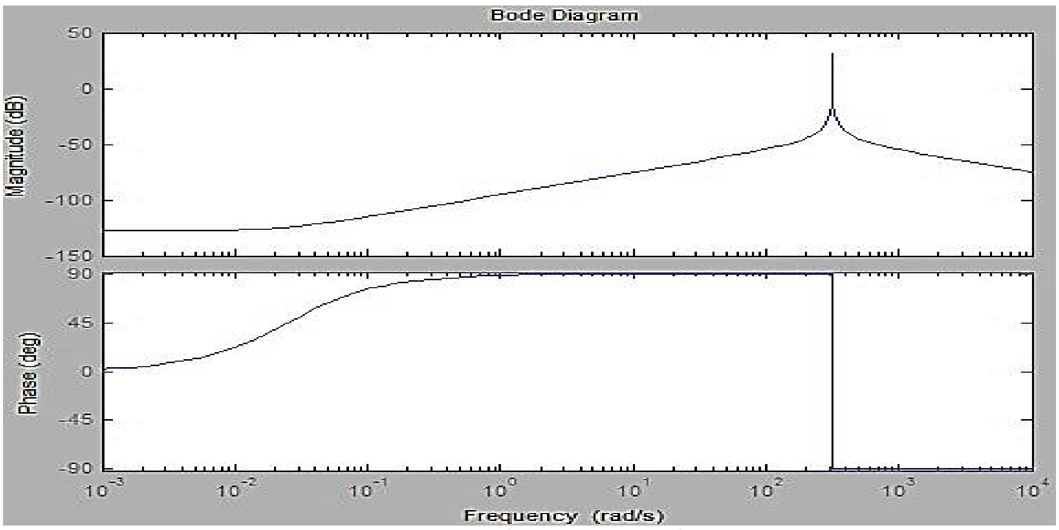

Fig. 19 bode plot of the sensitivity function

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 4, April 2016

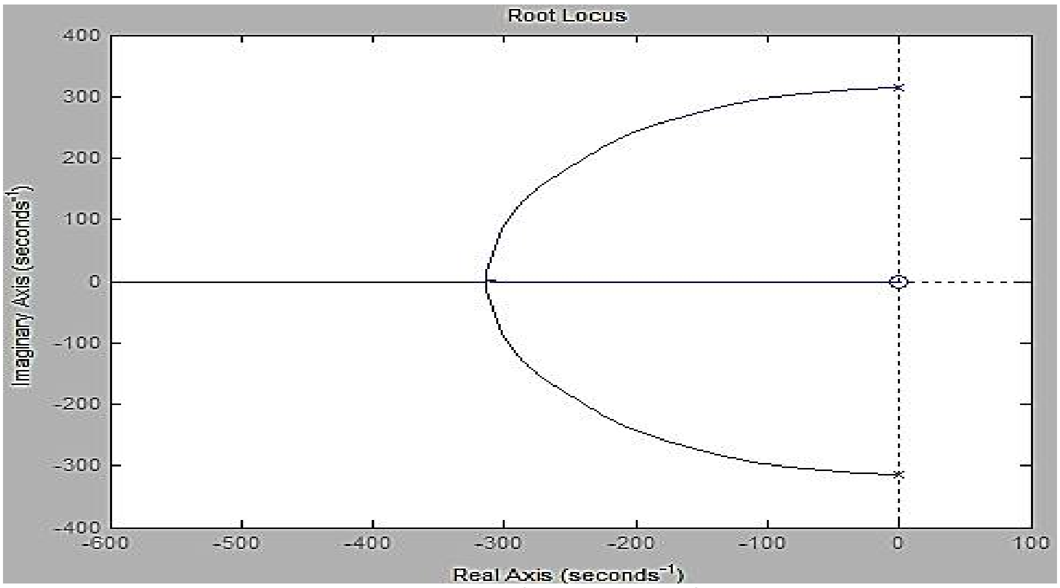

Fig. 20 Root locus of the sensitivity function

VII.CONCLUSION

Instead of high number of pulses of 3-phase inverters, the multilevel inverter with proper switching sequence also reduces the THD and gives better unbalanced control with sequence components. Sequence component magnitudes are increased by connecting the STATCOM to the system. The sensitivity of transfer function can also be used for controlling the STATCOM under balanced loads .

REFERENCES

[1] K.K Mohapatra, K.Gopakumar, V.T.Somasekar, " A harmonic elimination and suppression scheme for an open-end winding induction motor drive " IEEE Trans. Industrial electronics 2003 ,vol.50, no.6 , pp 1187-1198

[2] N.N.V. SurendraBabu , B.G.Fernandes," Cascaded two level inverter –based Multilevel STATCOM for higher –power Application " IEEE Trans. Power delivery ,vol.29,no.3,pgs : 993-1001, March 2014

[3] N.N.V. SurendraBabu , D.Apparao, B.G.Fernandes," Asymmetrical dc link voltage balance of a cascaded two level inverter based STATCOM " proc. IEEE TENCON, 2010,PP.483-488

[4] Ranjan A.K., Bhaskar D.V ,Parida .N ," Analysis and Simulation of cascaded H-Bridge multilevel inverter using level shift PWM technique " IEEE Trans. Power Electronics

[5] N.G.Hingorani, L.Gyugyi," Understanding FACTS " , Newyork ,IEEE press,2001

[6] Clark Hockgraf,Robert H. Lasseter," STATCOM controls for operation with unbalanced voltages " , IEEE, 1997