Improvement of Power Quality Using Transformerless Cascaded STATCOM under Balanced / Un-Balanced Supply Conditions with Non- Linear Loads

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***Abstract*— The rapid development of power electronics technology provides opportunities to develop new power equipment to improve the performance of the actual power systems. STATCOM can provide fast and efficient reactive power support to maintain power system voltage stability. Based on the cascaded H-bridge structure, a new STATCOM control strategy under the conditions of unbalanced loads and asymmetric system voltage is proposed. It proposes a control algorithm that devotes itself not only to meeting the demand of reactive power but also to voltage balancing of multiple galvanically isolated and floating dc capacitors. The control algorithm based on a phase-shifted carrier modulation strategy is prominent in having no restriction on the cascade number. This control strategy can be used to both the unbalanced loads and the asymmetric system voltage, avoiding the over current of negative sequence current and the clusters' dc-side voltage unbalance due. The simulation results are obtained using MATLAB/SIMULINK software.**

***Keywords*— Low harmonic rectifier, power factor correction (PFC), single-stage single-switch rectifier, unity power factor (UPF).**

I. INTRODUCTION

The STATCOM (or SSC) is a shunt-connected reactive-power compensation device that is capable of generating or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. It is in general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. Specifically,the STATCOM considered in this project is a voltage source converter that, from a given input of dc voltage, produces a set of 3-phase ac-output voltages, each in phase with and coupled to the corresponding ac system voltage through a relatively small reactance. The dc voltage is provided by an energy-storage capacitor [5] [6].

A STATCOM can improve power-system performance in such areas as the following: The dynamic voltage control in transmission and distribution systems, The power-oscillation damping in power-transmission systems, The transient stability, The voltage flicker control and The control of not only reactive power but also (if needed) active power in the connected line, requiring a dc energy source. A STATCOM is analogous to an ideal synchronous machine, which generates a balanced set of three sinusoidal voltages—at the fundamental frequency—with controllable amplitude and phase angle. This ideal machine has no inertia, is practically instantaneous, does not significantly alter the existing system impedance, and can internally generate reactive (both capacitive and inductive) power.

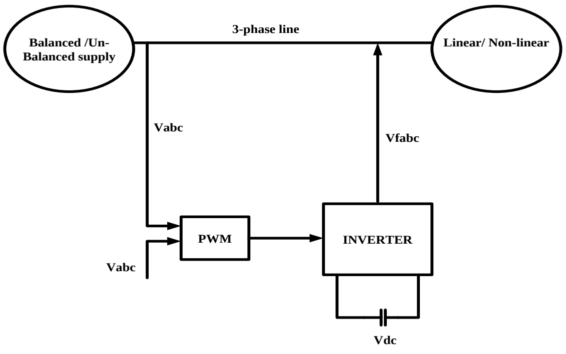

Fig. 1 STATCOM Principal Diagram

Among the FACTS (Flexible AC Transmission Systems) devices there exits the STATCOM (Static synchronous Compensator) that is a shunt device connected to the grid. This device allows increasing the capability of transmission line and maintaining voltage stability by either delivering or absorbing the reactive power. STATCOM consists of a power converter linked to AC main through an inductance. From [1] to [8] is shown that cascade multi-cell converters are a good choice for working as a STATCOM, but the main problem, with these converters, is to maintain DC links well regulated in order to assure the right performance of the STATCOM. This problem is due to the losses in each cell are different. When the DC link voltages are the same for each cell, the converter is called symmetrical one, and when these voltages maintain either 2:1 or 3:1 DC voltage relation between consecutives cells, the converter is called asymmetrical one. The main advantages for asymmetrical converters over symmetrical ones are that this converters can drive grater amount of power and they can reduce the harmonic current distortion since with this asymmetrical converters is possible to achieve output voltage with more levels than the symmetrical ones. However, the DC regulation problem for these asymmetrical converters increases because now not only the losses are different in each cell but also the DC link voltages.

This paper proposes a control method for cascaded H-bridge STATCOM under the condition of unbalance, which is injecting appropriate zero sequence voltage into the reference voltage in order to eliminate influence of the unbalance compensated current and asymmetrical voltage, making the active power exchange among the three-phase clusters[12]. Through the analysis of the result from compensated the unbalanced current, we can get a conclusion that when the same active power flow in to each cluster, the unbalance of dc-side voltage among the clusters will occur. In order to prove the feasibility of the proposed method, simulation is carried out by using MATLAB.

II. IMPACT OF UNBALANCE

A. *Cascaded STATCOM and Direct Current Control*

Cascaded STATCOM has two ways of cluster connection, one is Delta connection, and another is WYE connection. The clusters using Delta connection can be injected zero sequence current and the one using WYE connection can be injected zero sequence voltage, and each of the two ways has its own characteristics. This paper takes the WYE connection as an example to show how the cascaded STATCOM compensates the unbalanced current and voltage. The proposed method is suitable for both Delta and WYE connection, what to do is only change the injected zero sequence voltage to zero sequence current.

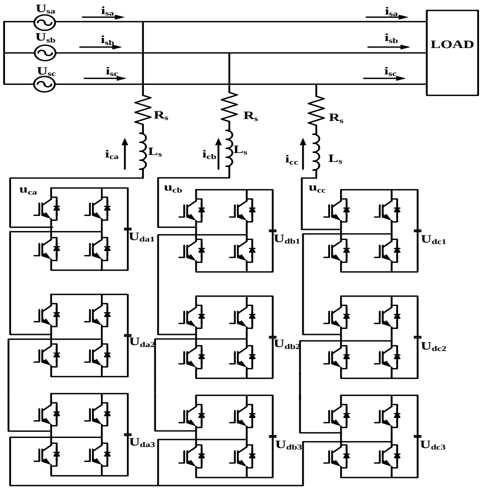

Fig. 2 Main structure of cascaded STATCOM

The cascaded H-bridge STATCOM topology of clusters using WYE connection which is shown in figure 2, both the neutral-point of the system and load are not grounded. Assume that the switch devices work in ideal condition. The connection inductance of between STATCOM and system is L_s, and the resistance equivalent to the loss of STATCOM is R_s. The voltages of the system are u_{sa}, u_{sb}, u_{sc}, the currents of the system are i_{sa}, i_{sb}, i_{sc}, the currents of compensation are i_{ca}, i_{cb}, i_{cc}, and the currents of load are i_{la}, i_{lb}, i_{lc}.

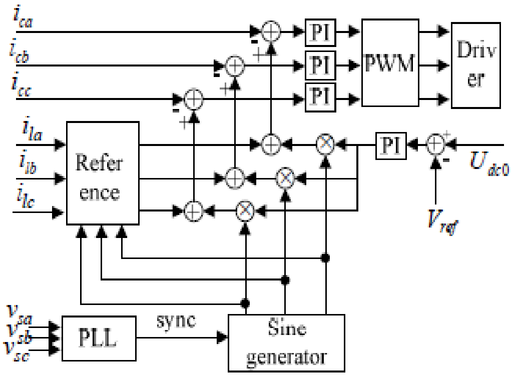

Fig. 3 Schematic diagram of the direct current control.

The schematic diagram of the direct current control is shown in figure 3. There are two control loops, one is inner loop controller and another is outer-loop controller in this control strategy, with the inner-loop making the output current of STATCOM track the reference current and the outer-loop maintaining the dc-side voltage stable. The modulation method is phase shift carrier modulation PWM. Among them：

$$U_{dc0} = \frac{1}{3}\left(\overline{U_{Da}} + \overline{U_{Db}} + \overline{U_{Dc}}\right) \qquad (1)$$

$$\overline{U_{Du}} = \frac{1}{N}\sum_{k=1}^{N} U_{Duk}, u = a, b, c \qquad (2)$$

B. *Compensation of the Unbalanced Current*

The schematic diagram of single phase equivalent circuit is shown in figure 4, and $i_c = i_u^+ + i_u^-$. Its phasor diagram is shown in figure 5:

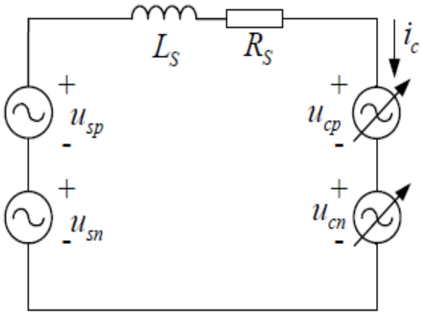

Fig. 4 Schematic diagram of single phase

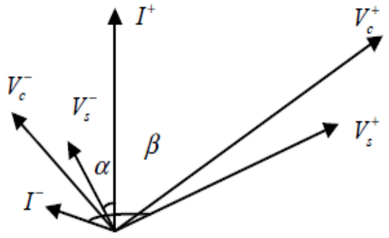

Fig. 5 Phasor diagram of current for compensation

Take phase A as an example, the system voltage and the output current and voltage of STATCOM are expressed as positive sequence and negative sequence, in which V_s^- and V_c^- are the positive and the negative sequence voltage of system and STATCOM, and I^+ *and* I^- are the positive and negative sequence current of STATCOM. Assume that the angle between positive sequence voltage and negative sequence current of phase A is β . The effect that the positive sequence voltage makes on the negative sequence current is shown as follows:

$$\begin{aligned} P_a^{pn} &= \overline{V_c^+} \times \overline{I^-} = V_c^+ \cdot I^- \cos\beta \\ P_b^{pn} &= \overline{V_c^+} \times \overline{I^-} = V_c^+ \cdot I^- \cos(120^\circ - \beta) \\ P_c^{pn} &= \overline{V_c^+} \times \overline{I^-} = V_c^+ \cdot I^- \cos(240^\circ - \beta) \end{aligned} \qquad (3)$$

$$P^{pn} = P_a^{pn} + P_b^{pn} + P_c^{pn} = 0 \qquad (4)$$

The conclusion accords with the condition in which that the system voltage is unbalanced. In the cascaded STATCOM, the capacitors of dc-side are independent with each other. As for a concerned phase, the effect that the positive sequence voltage on the negative sequence current is not equal to zero, what's more, the effect among the three phases are different. The effect that the negative sequence voltage on the positive sequence current cannot be neglected, which leads to the unbalance of active power in the three-phase clusters, and then results in the unbalance of dc-side capacitor voltage among the three-phase clusters, which threatening the safety of the equipment. What we can get from formula (3) and (4) is that the larger of the current for compensation, the stronger of the effect that the negative sequence voltage on the positive sequence current. The result from this is that the degree of the unbalance of dc side voltage will become more serious, so it is necessary to solve the problem of the dc-side voltage unbalancing and to improve the existing algorithm applied to the cascaded H-bridge STATCOM.

C. The Proposed Control Strategy

According to the basic principle of cascaded STATCOM, this paper proposes the method of injecting the zero sequence voltage. Using the principle that the effect of the three-phase compensation current on the zero sequence voltage in one cycle equals to zero ,but to certain phase is different to regulate the unbalance dc-side voltage which caused by the unbalanced current or asymmetrical system voltage, thus realizing the compensation of unbalance current and asymmetry. The basic principle of STATCOM is shown as (5) below

$$\begin{aligned} u_{sab} &= L_s \frac{di_a}{dt} + R_s i_{ca} + u_{ca} - L_s \frac{di_b}{dt} - R_s i_{cb} - u_{cb} \\ u_{sbc} &= L_s \frac{di_b}{dt} + R_s i_{cb} + u_{cb} - L_s \frac{di_c}{dt} - R_s i_{cc} - u_{cc} \\ u_{sca} &= L_s \frac{di_c}{dt} + R_s i_{cc} + u_{cc} - L_s \frac{di_a}{dt} - R_s i_{ca} - u_{ca} \end{aligned} \qquad (5)$$

Assume that the currents needed to be compensated are I_{ca}=$I_{cam}\angle^{\varphi}$ira, I_{cb}=$I_{cbm}\angle^{\varphi}$irb, I_{cc}=$I_{ccm}\angle^{\varphi}$irc , in which r means reference. And the angles of these currents between the zero sequence voltages are φ_a, φ_b, φ_c respectively. The amplitude of zero sequence voltage is U_{om} , so the exchange of the active power caused by the zero sequence voltage is:

$$\begin{aligned} \frac{1}{2} C U_{dca}^2 - \frac{1}{2} C U_{dc0}^2 &= -I_{ca} U_{0m} \cos\varphi_a T_s \\ \frac{1}{2} C U_{dcb}^2 - \frac{1}{2} C U_{dc0}^2 &= -I_{cb} U_{0m} \cos\varphi_b T_s \\ \frac{1}{2} C U_{dcc}^2 - \frac{1}{2} C U_{dc0}^2 &= -I_{cc} U_{0m} \cos\varphi_c T_s \end{aligned} \qquad (6)$$

Assume that the direction of the current flows into STATCOM is positive direction. The dc-side voltage differences between each cluster and the average voltage are $\Delta U_{dca} = U_{dca} - U_{dc0}$, $\Delta U_{dcb} = U_{dcb} - U_{dc0}$, $\Delta U_{dcc} = U_{dcc} - U_{dc0}$. In the range with little deviation these formulas can be simplified as:

$$\begin{aligned} C U_{dc0} \Delta U_{dca} + \frac{1}{2} C \Delta U_{dca}^2 &= -I_{ca} U_{0m} \cos\varphi_a T_s \\ C U_{dc0} \Delta U_{dcb} + \frac{1}{2} C \Delta U_{dcb}^2 &= -I_{cb} U_{0m} \cos\varphi_b T_s \\ C U_{dc0} \Delta U_{dcc} + \frac{1}{2} C \Delta U_{dcc}^2 &= -I_{cc} U_{0m} \cos\varphi_c T_s \end{aligned} \qquad (7)$$

Neglecting the high order terms, ΔU_{dca}^2, ΔU_{dcb}^2 and ΔU_{dcc}^2 the formulas are linear:

$$\begin{aligned} C U_{dc0} \Delta U_{dca} &= -I_{ca} U_{0m} \cos\varphi_a T_s \\ C U_{dc0} \Delta U_{dcb} &= -I_{cb} U_{0m} \cos\varphi_b T_s \\ C U_{dc0} \Delta U_{dcc} &= -I_{cc} U_{0m} \cos\varphi_c T_s \end{aligned} \qquad (8)$$

The formulas with zero sequence voltage magnitude and phase are:

$$\begin{aligned} C U_{dc0} \Delta U_{dca} &= -\frac{1}{2} U_{0M} I_{ram} \cos(\varphi_0 - \varphi_{ira}) T_s \\ C U_{dc0} \Delta U_{dcb} &= -\frac{1}{2} U_{0M} I_{rbm} \cos(\varphi_0 - \varphi_{irb}) T_s \\ C U_{dc0} \Delta U_{dcc} &= -\frac{1}{2} U_{0M} I_{rcm} \cos(\varphi_0 - \varphi_{irc}) T_s \end{aligned} \qquad (9)$$

Division of two sides, we get:

$$\frac{\Delta U_{dca}}{\Delta U_{dcb}} = \frac{I_{ram}\cos(\varphi_0 - \varphi_{ira})}{I_{rbm}\cos(\varphi_0 - \varphi_{irb})}$$

In order to simplify,define the index $k_{pow} = \frac{\cos(\varphi_0 - \varphi_{ira})}{\cos(\varphi_0 - \varphi_{irb})}$ and $k_{pow} = \frac{\Delta U_{dca} I_{rbm}}{\Delta U_{dcb} I_{ram}}$

$$\varphi_0 = \tan^{-1}\left(-\frac{\cos\varphi_{ira} - k_{pow}\cos\varphi_{irb}}{\sin\varphi_{ira} - k_{pow}\sin\varphi_{irb}} \right) \tag{10}$$

If cos φ_{ira} and cos φ_{irb} are negative and the sign symbols of the equation are opposite, the phase should be added a π:

$$\varphi_0 = \pi + \tan^{-1}\left(-\frac{\cos\varphi_{ira} - k_{pow}\cos\varphi_{irb}}{\sin\varphi_{ira} - k_{pow}\sin\varphi_{irb}} \right) \tag{11}$$

The amplitude of the zero sequence voltage is:

$$U_{0M} = \left| \frac{2CU_{d0}\Delta U_{da}}{T_s\cos(\varphi_0 - \varphi_{ira}) I_{ram}} \right| \tag{12}$$

According to the control strategy proposed above, the strategy can be divided into three parts. They are control loop of current tracking, control loop of dc-side voltage control and control loop of the zero sequence voltage's injection. The current loop and dc-side voltage loop remain unchanged. The control strategy of injecting zero sequence voltage proposed is shown in figure 6, which adopts the PI control.

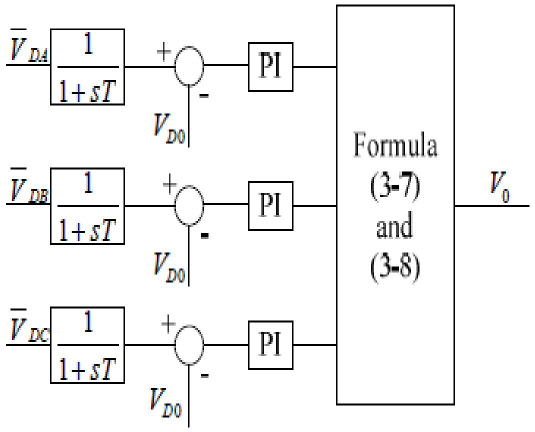

Fig. 6 Diagram of the principle of the proposed control strategy

III. MATLAB MODELING AND SIMULATION RESULTS

The STATCOM model is established based on Matlab/Simulink. The model parameters are listed as following: The grid voltage is 2500V, 50Hz. The inductor is 10mH and the DC capacitor is 5000IlF. The reference DC voltage is 1000V. Each phase of the inverter is constructed by 3 cascade H-bridges. The current reference is set to 150A and the voltage reference 1500V. Here simulation is carried out in different cases such as Balanced and Unbalanced Load Conditions with linear & Non-Linear Load condition.

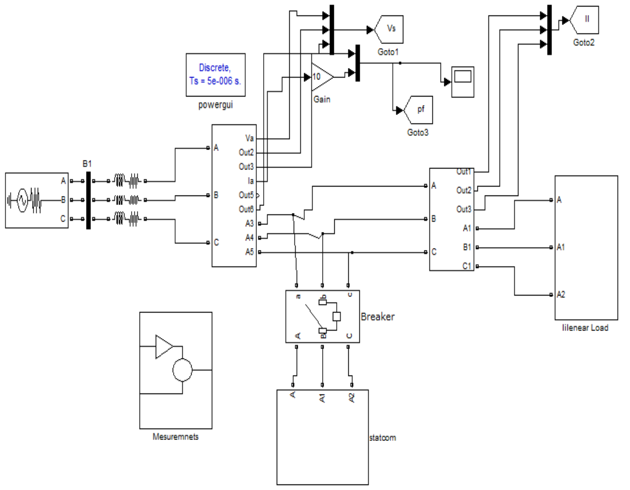

Fig. 7 Matlab/Simulink Model of Proposed 7 Level Cascaded Multilevel Based STATCOM

Fig.7 shows the Matlab/Simulink Model of Proposed 7 Level Cascaded Multilevel Based STATCOM with different load conditions such as balanced, unbalanced load conditions.

Case1: Proposed Compensator with Balanced Non-Linear Load Condition.

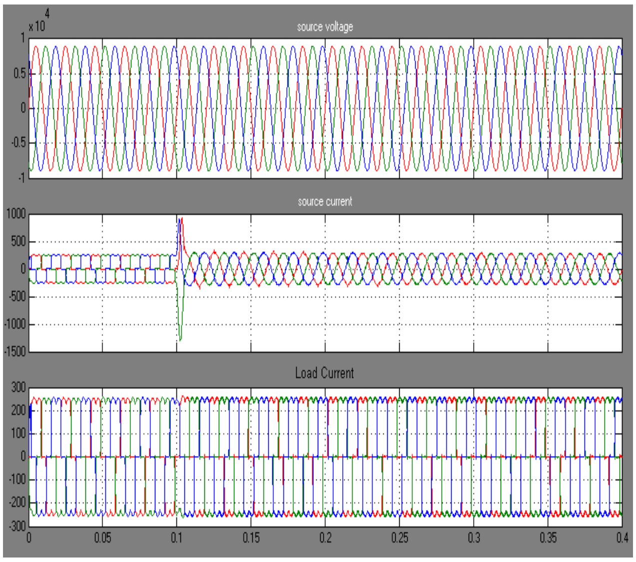

Fig. 8 Source Voltage, Source Current, Load Current

Fig.8 shows the Source Voltage, Source Current, Load Current of balanced Non-linear load condition with Compensator.

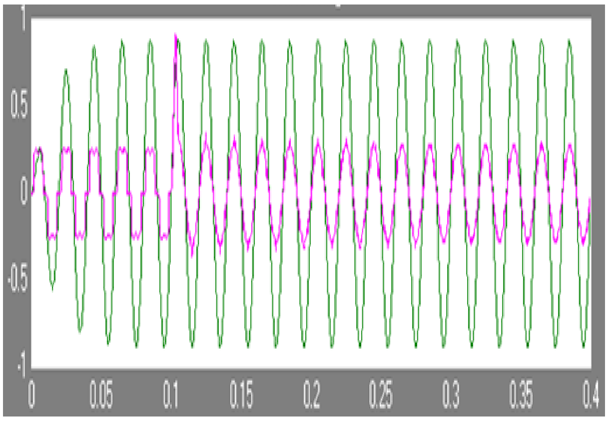

Fig. 9 Source Power Factor

A Fig.9 show the source side power factor is unity condition, due to Non-linear load, source current somewhat distorts, before compensator is at on condition.

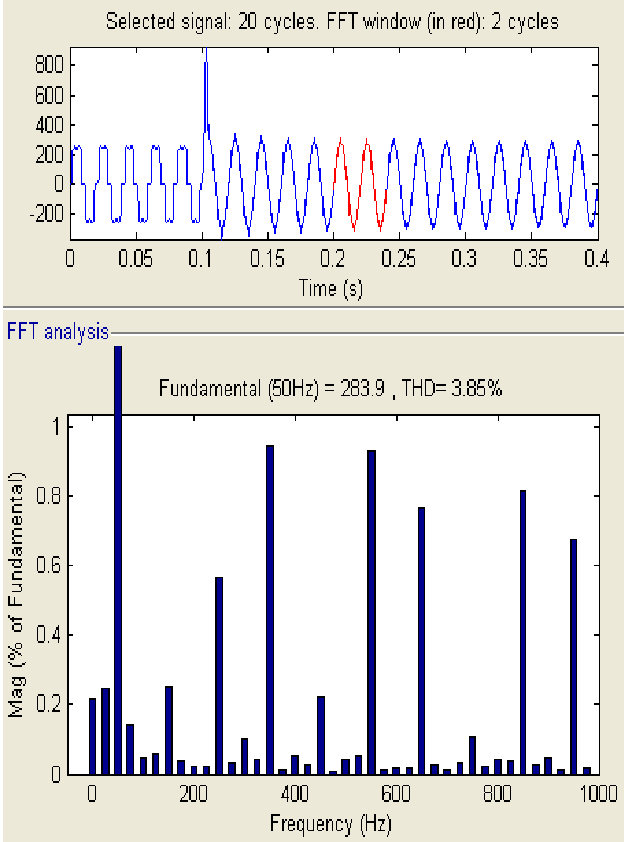

Fig. 10 FFT Analysis of Phase A Source Current with Balanced Non-Linear Load Condition

Fig.10 shows the FFT Analysis of Phase A Source Current with Balanced Non Linear Load Condition, we get THD 3.85%.

Case 2: Proposed Compensator with Un-Balanced Non-Linear Load Condition.

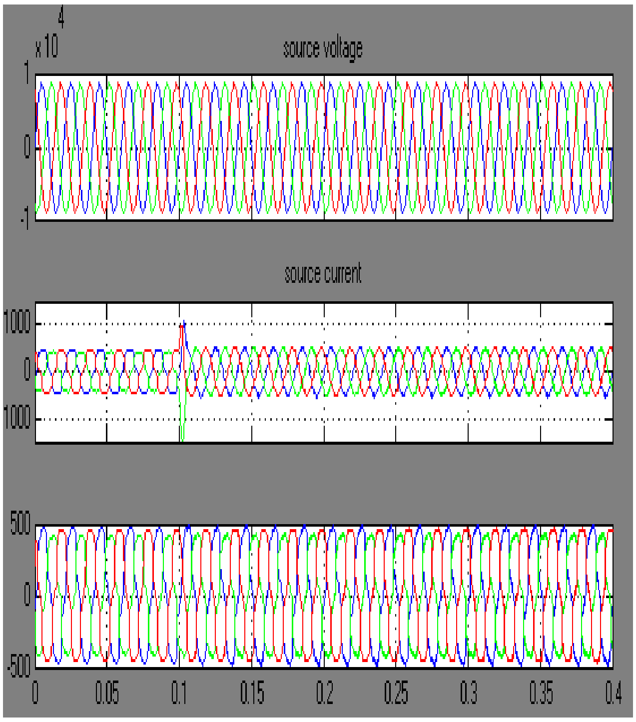

Fig. 11 Source Voltage, Source Current, Load Current

Fig.11 shows the Source Voltage, Source Current, Load Current of unbalanced Non-linear load condition with Compensator.

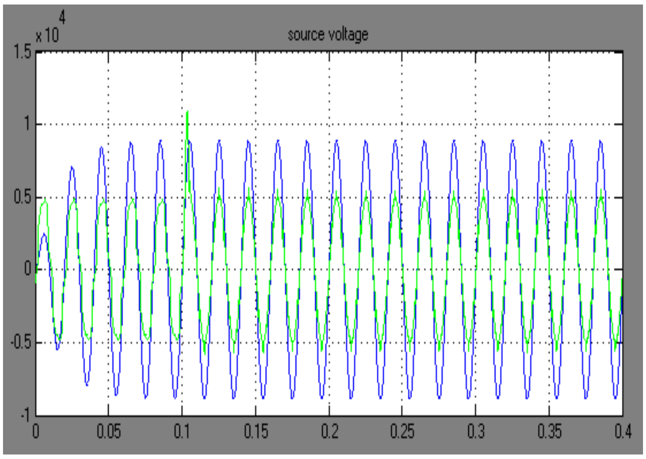

Fig. 12 Source Power Factor

A Fig.12 show the source side power factor is unity condition, due to Unbalanced Non-linear load, source current somewhat distorts, before compensator is at on condition.

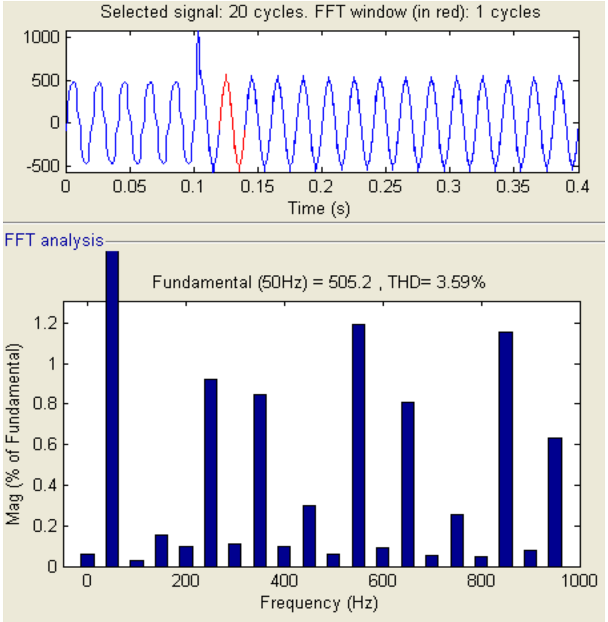

Fig. 13 FFT Analysis of Phase A Source Current with Un Balanced Non Linear Load Condition

Fig.13 shows the FFT Analysis of Phase A Source Current with Un-Balanced Non Linear Load Condition, we get THD 3.59%.

Note: Source Current with Balanced Linear Load Condition, we get THD 2.14%.

Source Current with Un-Balanced Linear Load Condition, we get THD 1.10%.

By the simulations resultsn THD is slightly more for non-linear load conditions campare to linear load conditions.

IV. CONCLUSION

The multilevel voltage source inverter is recently applied in many industrial applications such as ac power supplies, static VAR compensators, drive systems, etc. One of the significant advantages of multilevel configuration is the harmonic reduction in the output waveform without increasing switching frequency or decreasing the inverter power outputCascade H-bridge multilevel inverter has the advantages of simple structure and little harmonic content. Simulation results verify the compensation function and dynamic response of STATCOM based on the control strategy with different load conditions are introduced in this paper, which indicates a from prospect of the device in high-power applications, THD also well within IEEE standards.

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