

Comparison of Various Levels of Cascaded MLI based DSTATCOM for Compensation of Harmonics and Reactive Power using Reference Control Strategy

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Abstract: The “multilevel converter” has drawn tremendous interest in the power industry. The general structure of the multilevel converter is to synthesize a sinusoidal voltage from several levels of voltages, Multilevel voltage source converters are emerging as a new breed of power converter options for high power applications, These converter topologies can generate high-quality voltage waveforms with power semiconductor switches operating at a frequency near the fundamental. Among the available multilevel converter topologies, the cascaded multilevel converter constitutes a promising alternative, providing a modular design that can be extended to allow a transformer less connection. This paper presents a three-phase, five-level and seven level cascaded multilevel voltage source inverter based active filter for power line conditioning to improve power quality in the distribution network. The active filter compensates both reactive power and harmonic currents drawn by non-linear loads; additionally it facilitates power factor corrections. The compensation process is based on concept of p-q theory. This proposed cascaded five level and seven level active power filter system is validated through MATLAB/SIMULINK Platform.

Keywords- DSTATCOM, Instantaneous power theory, Power quality, Triangular-sampling current modulator, Cascaded H- Bridge Multilevel Inverter.

I. Introduction

In recent years Electrical Power Quality had obtained more attention in power engineering. In present day's power distribution systems is suffering from severe power quality problems. These power quality problems include high reactive power burden, harmonics currents, load unbalance, excessive neutral current etc. The measure of power quality depends upon the needs of the equipment that is being supplied. What is good power quality for an electric motor may not be good enough for a personal computer. Usually the term power quality refers to maintaining a sinusoidal waveform of bus voltages at rated voltage and frequency [1]. The waveform of electric power at generation stage is purely sinusoidal and free from any distortion. Many of the Power conversion and consumption equipment are also designed to function under pure sinusoidal voltage waveforms. However, there are many devices that distort the waveform. These distortions may propagate all over the electrical network. In recent years, there has been an increased use of non-linear loads which has resulted in an increased fraction of non-sinusoidal currents and voltages in Electric Network. The wave shape phenomena associated with power

quality may be characterized into synchronous and non synchronous phenomena. Synchronous phenomena refer to those in synchronism with A.C waveform at power frequency [2],[3].

A group of controllers together called Custom Power Devices (CPD), which include the DSTATCOM (distribution static compensator), The DSTATCOM, is a shunt-connected device, which takes care of the power quality problems in the currents. It consists of a dc capacitor, three-phase inverter (IGBT, thyristor) module, ac filter, coupling transformer and a control strategy. The basic electronic block of the D-STATCOM is the voltage-sourced inverter that converts an input dc voltage into a three-phase output voltage at fundamental frequency. The D-STATCOM employs an inverter to convert the DC link voltage V_{dc} on the capacitor to a voltage source of adjustable magnitude and phase. Therefore the D-STATCOM can be treated as a voltage-controlled source. The D-STATCOM can also be seen as a current-controlled source. The generalized instantaneous reactive power theory which is valid for sinusoidal or non-sinusoidal and balanced or unbalanced three-phase power systems with or without zero-sequence currents were later proposed [4-8]. The construction controller of the D-STATCOM is used to operate the inverter in such a way that the phase angle between the inverter voltage and the line voltage is dynamically adjusted so that the D-STATCOM generates or absorbs the desired VAR at the point of connection. The phase of the output voltage of the thyristor-based inverter, V_i , is controlled in the same way as the distribution system voltage, V_s .

The DSTATCOM is based on the instantaneous real-power theory; it provides good compensation characteristics in steady state as well as transient states [9-11]. The instantaneous real-power theory generates the reference currents required to compensate the distorted line current harmonics and reactive power. It also tries to maintain the dc-bus voltage across the capacitor constant. Another important characteristic of this real-power theory is the simplicity of the calculations, which involves only algebraic calculation [12-17].

A multilevel inverter can reduce the device voltage and the output harmonics by increasing the number of output voltage levels. There are several types of multilevel inverters: cascaded H-bridge (CHB), neutral point clamped, flying capacitor. In particular, among these topologies, CHB inverters are being widely used because of their modularity and simplicity. Various modulation methods can be applied to CHB inverters. CHB inverters can also increase the number of output voltage levels easily by increasing the number of H-bridges. This paper presents a DSTATCOM with a proportional integral controller based CHB multilevel (five level and seven level) inverter for the harmonics and reactive power mitigation of the nonlinear loads. This type of arrangements have been widely used for PQ applications due to increase in the number of voltage levels, low switching losses, low electromagnetic compatibility for hybrid filters and higher order harmonic elimination.

Instantaneous real-power theory based cascaded multilevel inverter based DSTATCOM is connected in the distribution network at the PCC through filter inductances and operates in a closed loop. The DSTATCOM system contains a cascaded inverter, RL-filters, a compensation controller (instantaneous real-power theory) and switching signal generator (proposed triangular-sampling current modulator) as shown in the Figure 1.

II.PROPOSED SYSTEM

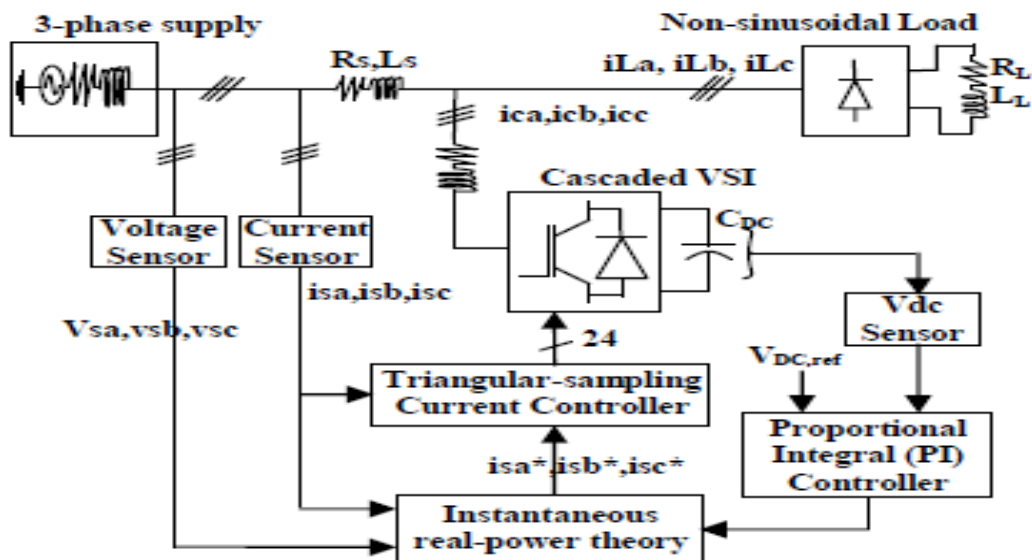


Figure 1: Schematic Diagram of DSTATCOM

The three-phase supply source connected with non-linear load and these nonlinear loads currents contains fundamental and harmonic components. If the active power filter provides the total reactive and harmonic power, $i_s(t)$ will be in phase with the utility voltage and would be sinusoidal. At this time, the active filter must provide the compensation current therefore; active power filter estimates the fundamental components and compensating the harmonic current and reactive power.

A. Five level CHB Inverter:

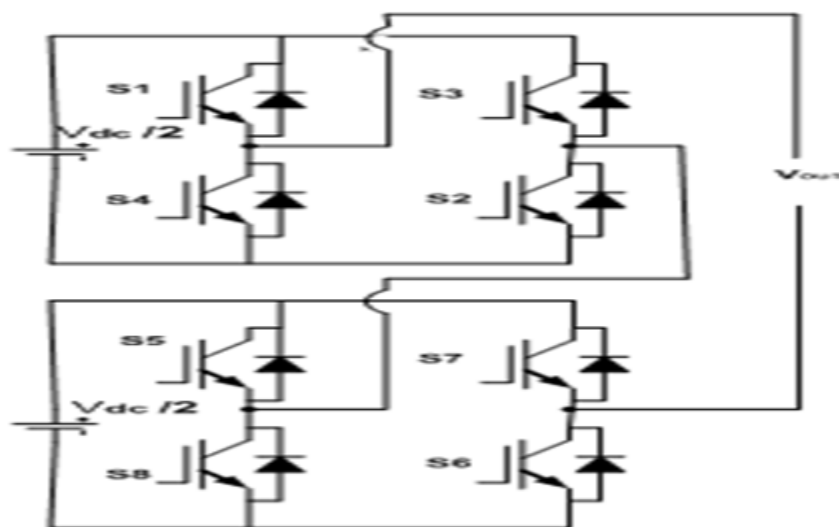


Figure.2 Five level CHB inverter

Figure 2 Shows the five level multilevel inverter and Table I shows the switching states of the 5 level inverter. Here even though we have eight switches at any switching state only two switches are on/off at a voltage level of $V_{dc}/2$, so switching losses are reduced. In three level inverter dv/dt is V_{dc} , but in five level inverter dv/dt is $V_{dc}/2$. As dv/dt reduces the stress on switches reduces and EMI reduces.

Table I Switching table for Full H-Bridge of five level inverter

Switches Turn ON	Voltage Level
S1,S2,S6,S8	$V_{dc}/2$
S1,S2,S5,S6	V_{dc}
S2, S4,S6,S8	0
S3,S4,S6,S8	$-V_{dc}/2$
S3,S4,S7,S8	$-V_{dc}$

B Seven level CHB Inverter:

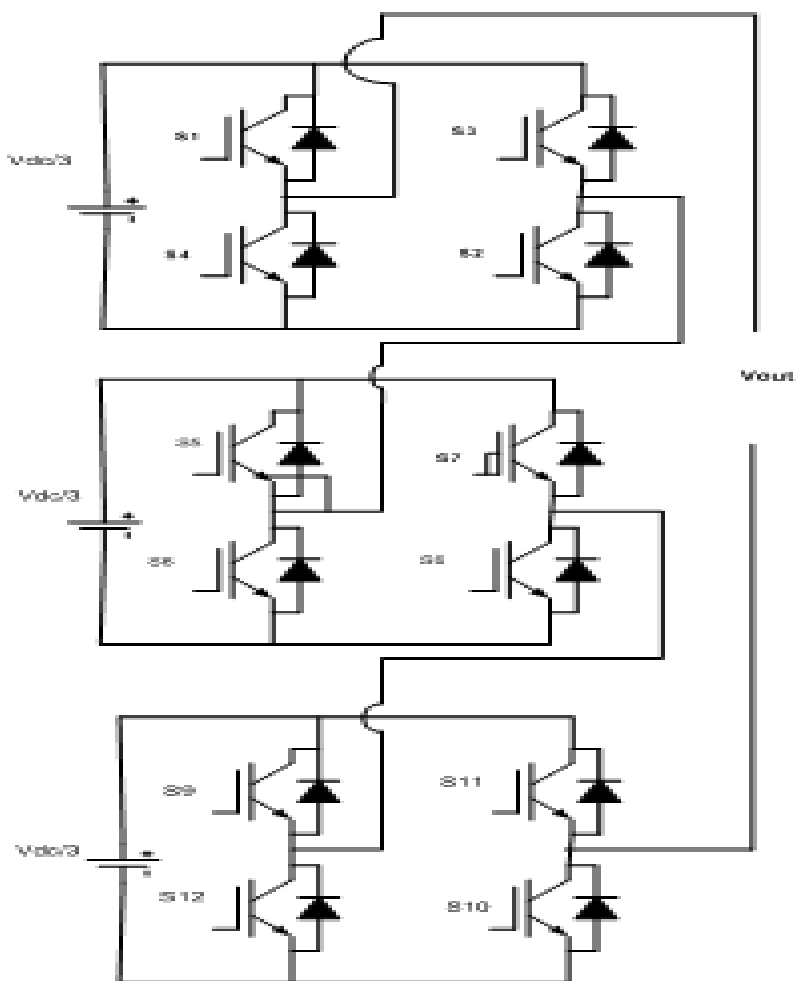


Figure. 3 Seven level CHB inverter

Figure 3 Shows the seven level multilevel inverter and Table shows the switching states of the seven level inverter

Table II Switching table for Full H-Bridge of seven level inverter

Switches Turn ON	Voltage Level
S1,S2,S6,S8,S10,S12	$V_{dc}/3$
S1,S2,S5,S6,S10,S12	$2V_{dc}/3$
S1,S2,S5,S6,S9,S10	V_{dc}
S2,S4,S6,S8,S10,S12	0
S3,S4,S6,S8,S10,S12	$-V_{dc}/3$
S3,S4,S7,S8,S10,S12	$-2V_{dc}/3$
S3,S4,S7,S8,S11,S12	$-V_{dc}$

III. REFERENCE CURRENT CONTROL STRATEGY SYSTEM:

The control scheme of the shunt active power filter must calculate the current reference signals from each phase of the inverter using instantaneous real-power compensator. The block diagram as shown in Figure.4, that control scheme generates the reference current required to compensate the load current harmonics and reactive power. The PI controller is tried to maintain the dc-bus voltage across the capacitor constant of the cascaded inverter. This instantaneous real- power compensator with PI-controller is used to extracts reference value of current to be compensated.

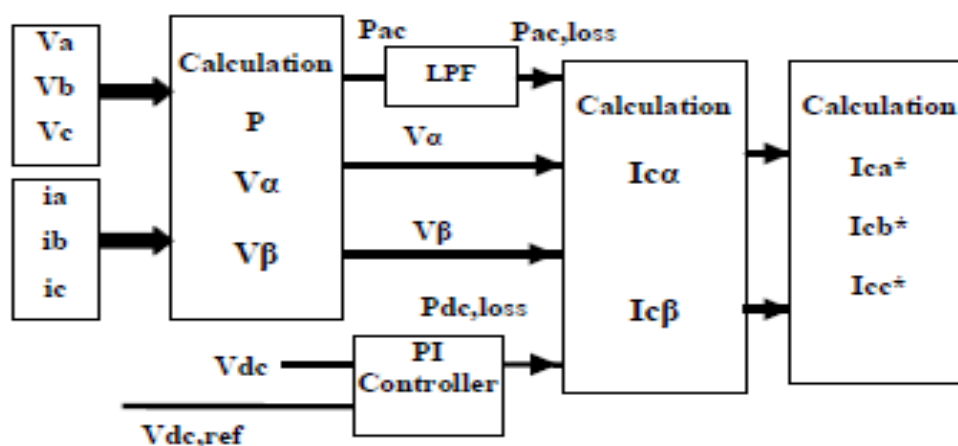


Figure 4: Reference current generator using instantaneous real-power theory

These reference currents i_{sa}^* , i_{sb}^* and i_{sc}^* are calculated instantaneously without any time delay by using the instantaneous α, β coordinate currents. The required references current derivate from the inverse Clarke transformation and it can be written as

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3/2} \\ -1/2 & -\sqrt{3/2} \end{bmatrix} \begin{bmatrix} i_{ca} \\ i_{c\beta} \end{bmatrix} \quad (1)$$

The reference currents (i_{sa}^* , i_{sb}^* and i_{sc}^*) are compared with actual source current i_{sa} , i_{sb} and i_{sc} that facilitates generating cascaded multilevel inverter switching signals using the proposed triangular-sampling current modulator. The small amount of real-power is adjusted by changing the amplitude of fundamental component of reference currents and the objective of this algorithm is to compensate all undesirable components. When the power system voltages are balanced and sinusoidal, it leads to constant power at the dc bus capacitor and balanced sinusoidal currents at AC mains simultaneously.

The p-q theory performs a Clarke transformation of a stationary system of coordinates a,b,c to an orthogonal reference system of coordinates α, β . In a,b,c coordinates axes are fixed on the same plane, apart from each other by 120 that as shown in Figure 5. The instantaneous space vectors voltage and current V_a, i_a are set on the a-axis, V_b, i_b are on the b axis, and V_c, i_c are on the c axis. These space vectors are easily transformed into α, β coordinates. The instantaneous source voltages V_{sa}, V_{sb}, V_{sc} are transformed into the α, β coordinate's voltage by Clarke transformation as follows:

$$v_{\alpha\beta 0} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & -\sqrt{3/2} \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} v_{abc} \quad (2)$$

Similarly, the instantaneous source current i_{sa}, i_{sb}, i_{sc} also transformed into the α, β coordinate's current by Clarke transformation that is given as:

$$i_{\alpha\beta 0} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & -\sqrt{3/2} \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} i_{abc} \quad (3)$$

Where α and β axes are the orthogonal coordinates. They V_α, i_α are on the α -axis, and V_β, i_β are on the β -axis.

Real-Power (P) calculation:

The orthogonal coordinates of voltage and current V_α, i_α are on the α -axis and V_β, i_β are on the β -axis. Let the instantaneous real-power calculated from the α -axis and β -axis of the current and voltage respectively. These are given by the conventional definition of real-power as:

$$P_{ac} = V_\alpha i_\alpha + V_\beta i_\beta \quad (4)$$

This instantaneous real-power p_{ac} is passed to first order Butterworth design based 50 Hz low pass filter (LPF) for eliminating the higher order components; it allows the fundamental

component only. These LPF indicates ac components of the real-power losses and it's denoted as P_{ac} .

The DC power loss is calculated from the comparison of the dc-bus capacitor voltage of the cascaded inverter and desired reference voltage. The proportional and integral gains (PI Controller) are determining the dynamic response and settling time of the dc-bus capacitor voltage. The DC component power losses can be written as

$$P_{DC (loss)} = [V_{DC, ref} - V_{DC}] \left[k_p + \frac{K_I}{s} \right] \quad (5)$$

The instantaneous real-power P is calculated from the AC component of the real-power loss p_{ac} and the DC power loss $P_{DC} (Loss)$; it can be defined as follows:

$$P = P_{ac} + P_{DC (Loss)} \quad (6)$$

The instantaneous current on the $\alpha\beta$ coordinates of $I_{c\alpha}$ and $i_{c\beta}$ are divided into two kinds of instantaneous current components; first is real-power losses and second is reactive power losses, but this proposed controller computes only the real-power losses. So the α, β coordinate currents $i_{c\alpha}$, $i_{c\beta}$ are calculated from the V_α , V_β voltages with instantaneous real power p only and the reactive power q is assumed to be zero. This approach reduces the calculations and shows better performance than the conventional methods. The α, β coordinate currents can be calculated as

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \quad (7)$$

From this equation, we can calculate the orthogonal coordinate's active-power current. The α - axis of the instantaneous active current is written as:

$$i_{\alpha p} = \frac{v_\alpha p}{v_\alpha^2 + v_\beta^2} \quad (8)$$

Similarly, the β - axis of the instantaneous active current is written as:

$$i_{\beta p} = \frac{v_\beta p}{v_\alpha^2 + v_\beta^2} \quad (9)$$

Let the instantaneous powers $P(t)$ in the α -axis and the β - axis is represented as P_α and P_β respectively. They are given by the definition of real-power as follows

$$P(t) = v_{\alpha p}(t) i_{\alpha p}(t) + v_{\beta p}(t) i_{\beta p}(t) \quad (10)$$

The AC and DC component of the instantaneous power $P(t)$ is related to the harmonics currents. The instantaneous real power generates the reference currents required to compensate the distorted line current harmonics and reactive power.

IV.MATLAB/SIMULINK MODELLING AND SIMULATION RESULTS

Here the simulation is carried out by three cases

1. Non-linear load Without Filter
2. Non-linear load with five level cascaded multilevel Active power filter
3. Non-linear load with seven level Cascaded multilevel Active power filter.

Case 1: Nonlinear load without Active power Filter:

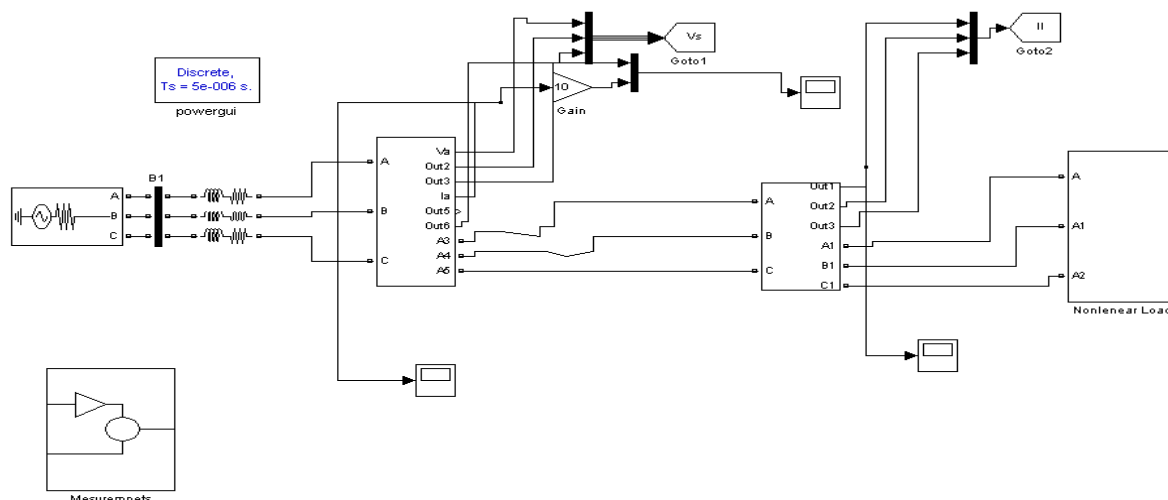


Figure 5: Matlab/Simulink model of nonlinear load without active filter

Figure-6 shows the three phase source voltages, three phase source currents and load currents respectively without Active power filter. It is clear that without Active power filter load current and source currents are same.

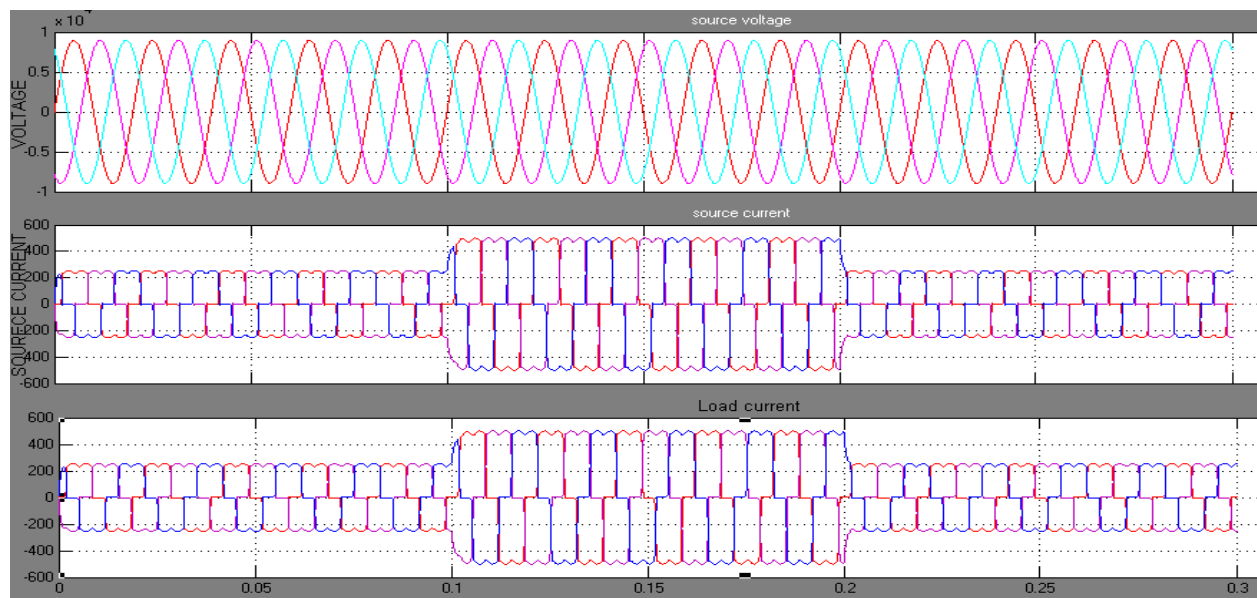


Figure 6: Source voltage, Source current, Load current

Case 2: Non-linear load with five level cascaded multilevel Active power filter

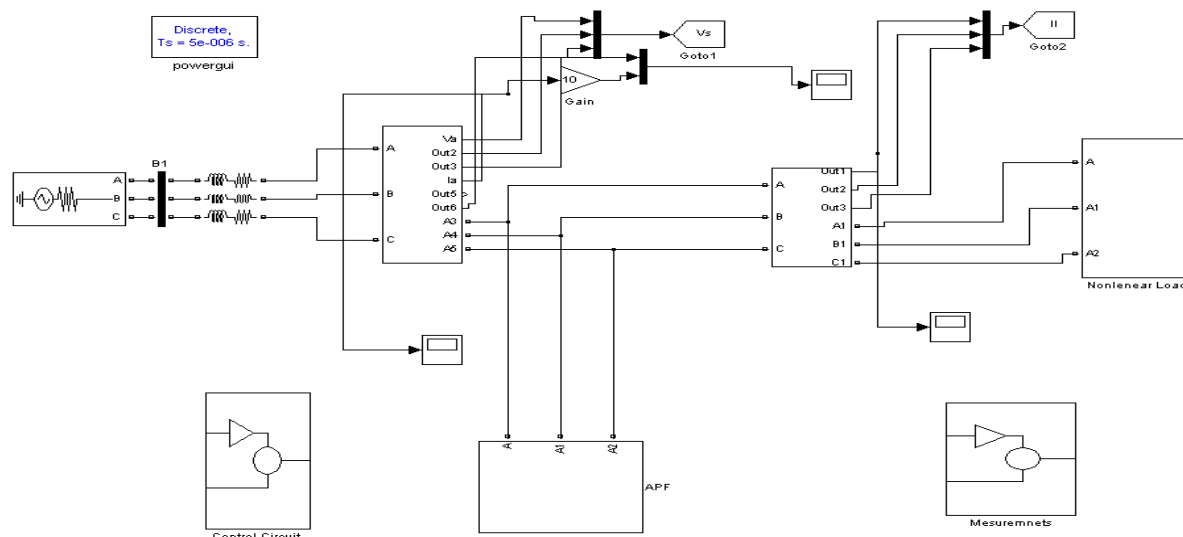


Figure 7: Matlab/Simulink Model of Nonlinear load with Five level Cascaded multilevel Active power filter

The performance of the proposed instantaneous real-power compensator cascaded five level multilevel inverter based active power filter is evaluated through Matlab/Simulink tools. The non-linear diode rectifier R-L load is connected with ac mains and cascaded active filter is connected in parallel at the PCC for injecting the anti-harmonics and eliminating the harmonics and improving the Reactive power.

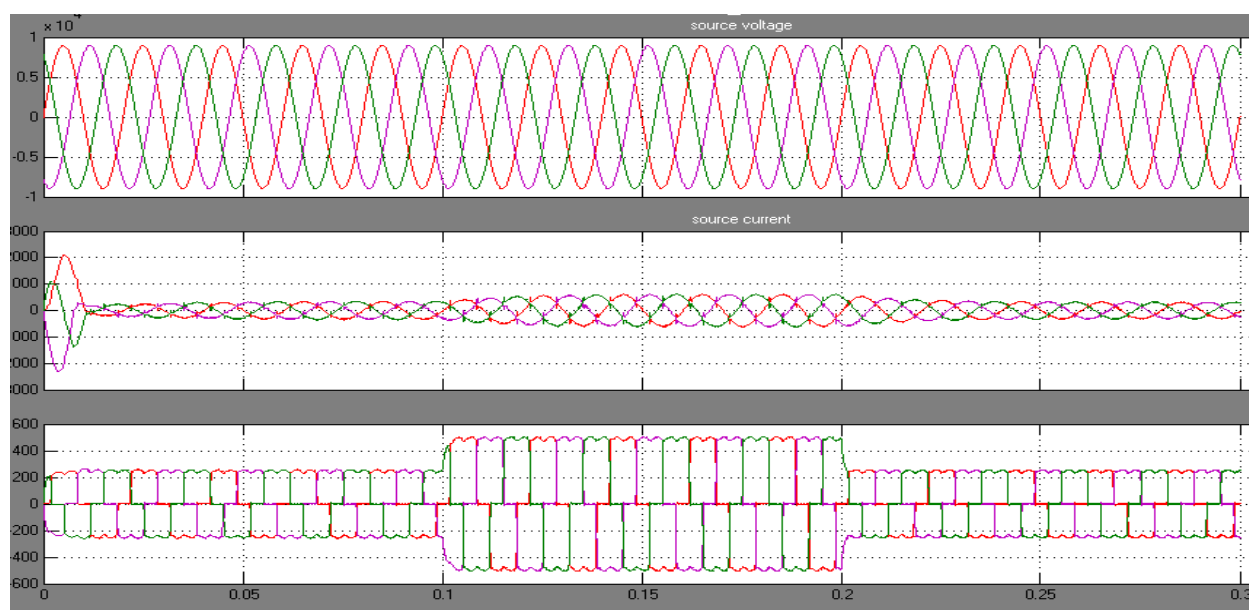


Figure 8: Source voltage, Source current, Load current

Figure-8 shows the three phase source voltages, three phase source currents and load currents respectively with Cascaded Multilevel five level Active power filter. It is clear that with Active power filter load current are same and source currents are compensated.

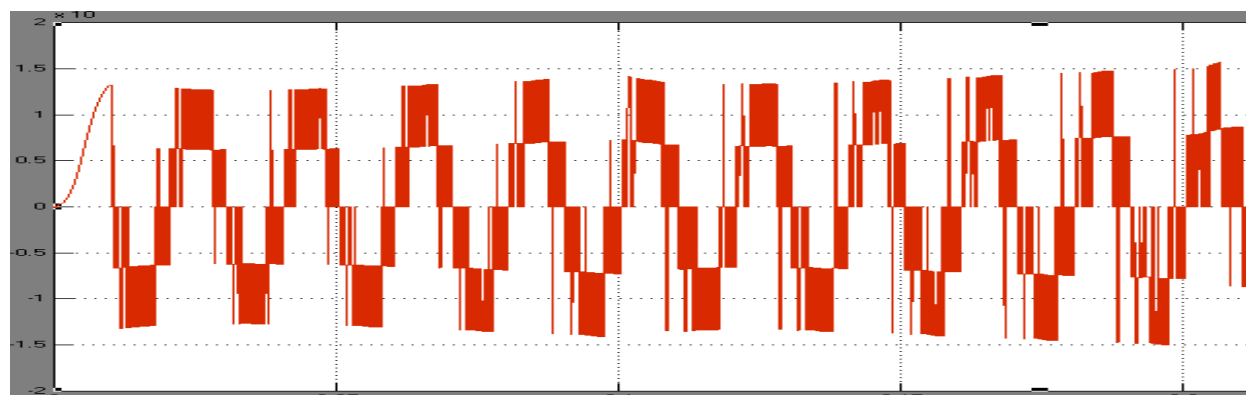


Figure 9: Five level output Voltage

Figure 9 Shows the Five level output voltage , when system is connected to cascaded five level multilevel active power filter.

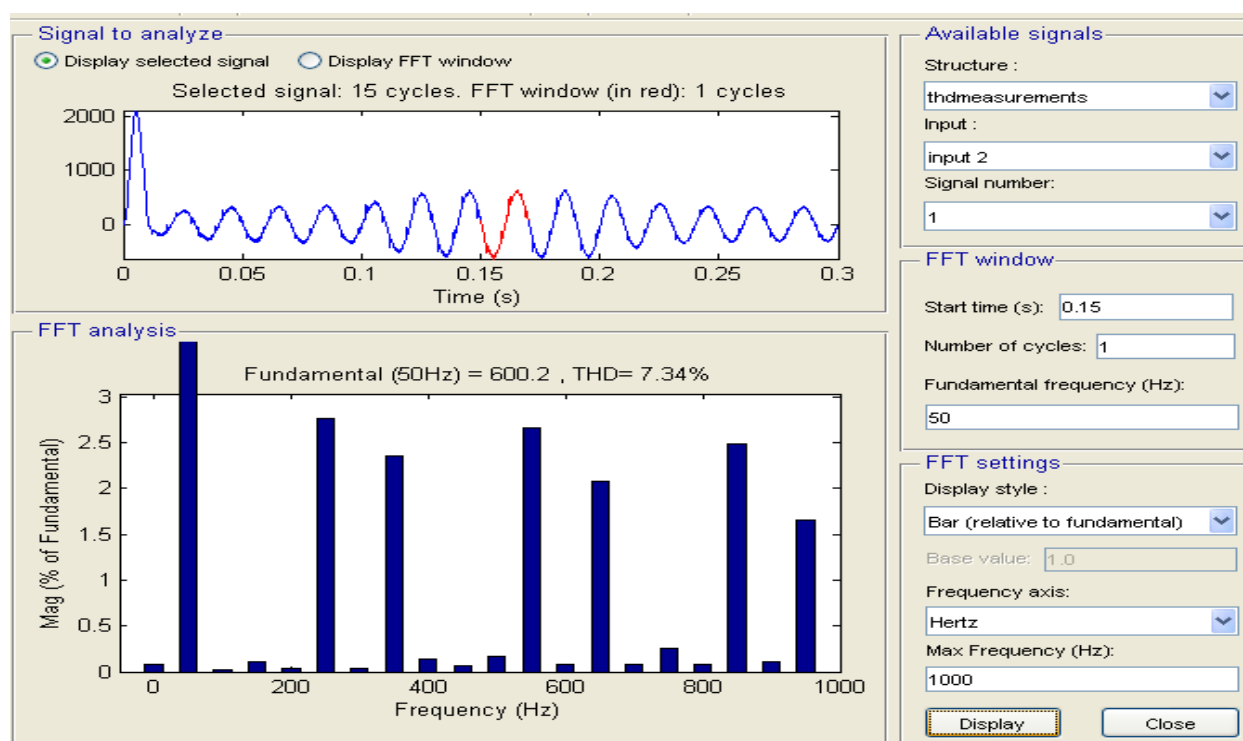


Figure-10 Harmonic spectrum of Phase-A Source current with Five level Active power filter

Figure-10 shows the harmonic spectrum of Phase –A Source current with cascaded Multilevel Five level active power filter. The THD of source current with seven level active filter is 7.34%.

Case 3: Non-linear load with Seven level Cascaded multilevel Active power filter

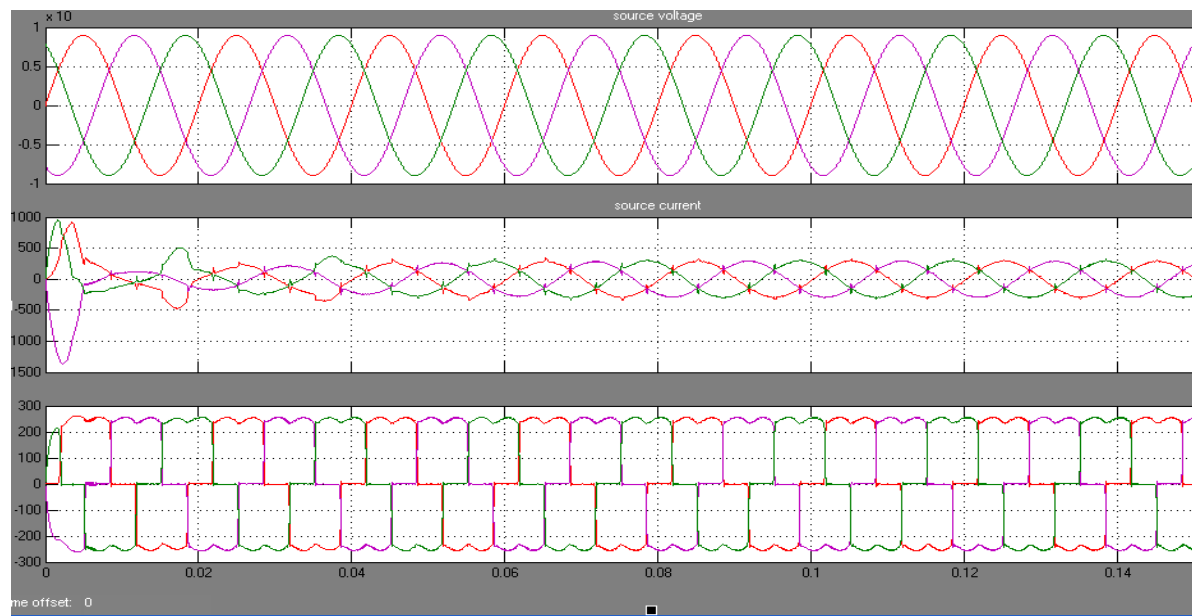


Figure 11: Source voltage, Source current, Load current

Figure-11 shows the three phase source voltages, three phase source currents and load currents respectively with Cascaded Multilevel Seven level Active power filter. It is clear that with Active power filter load current are same and source currents are compensated.

Figure 12 Shows the Seven level output voltage , when system is connected to cascaded five level multilevel active power filter.

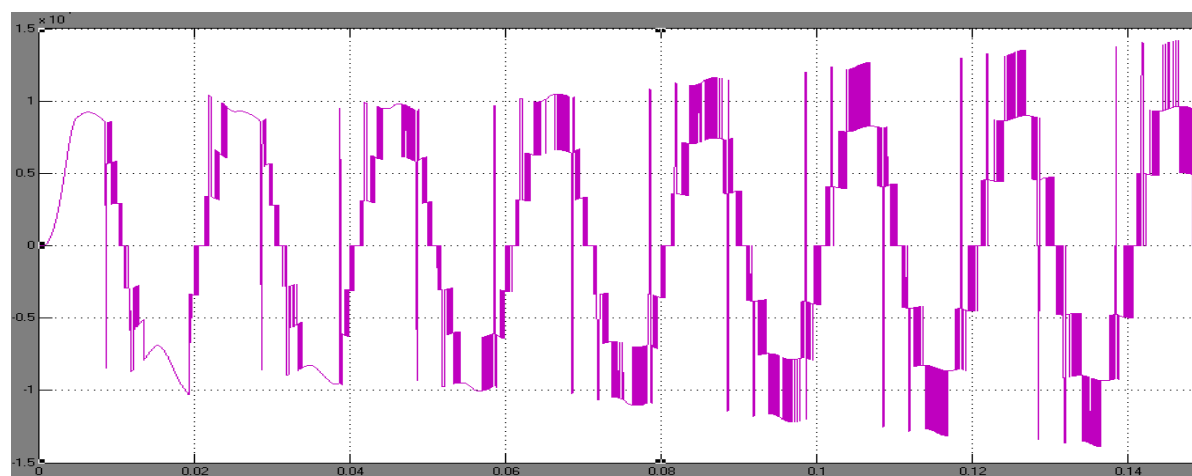


Figure 12. Seven level output Voltage

Figure 13 shows the power factor waveforms of the designed system without DSTATCOM. The waveform clearly shows that there is no unity power factor.

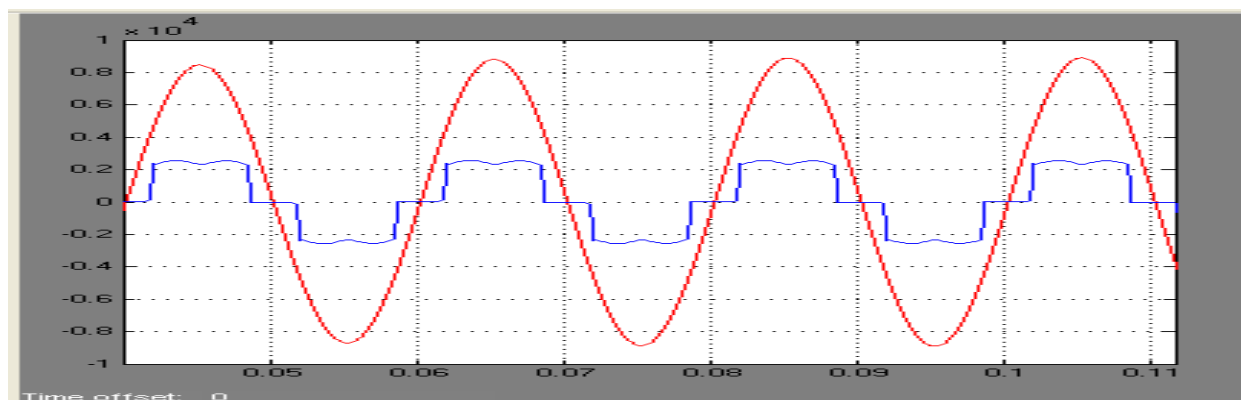


Figure 13: Power Factor without DSTATCOM

Figure 14 shows the power factor waveforms of the designed system with DSTATCOM. The waveform clearly shows that there is unity power factor where both the voltage and current are in phase.

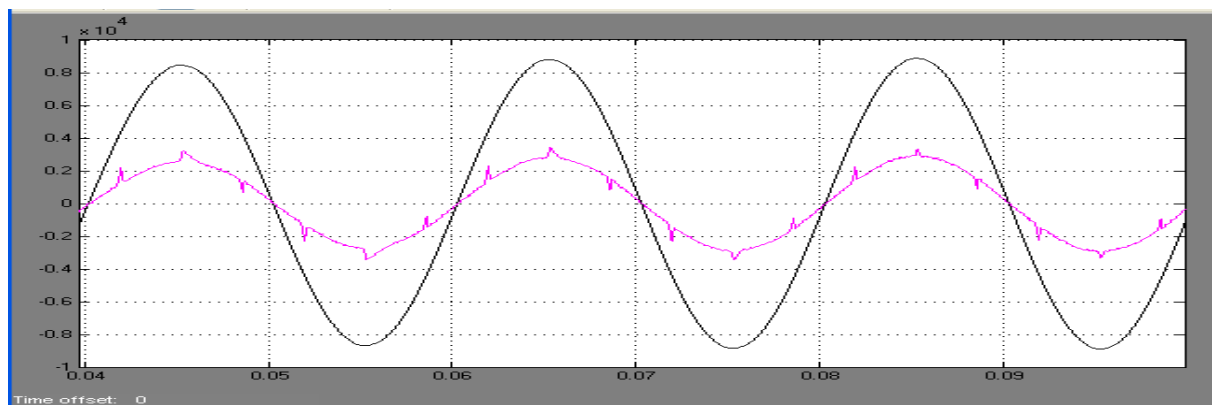


Figure 14: Unity power Factor with DSTATCOM connected

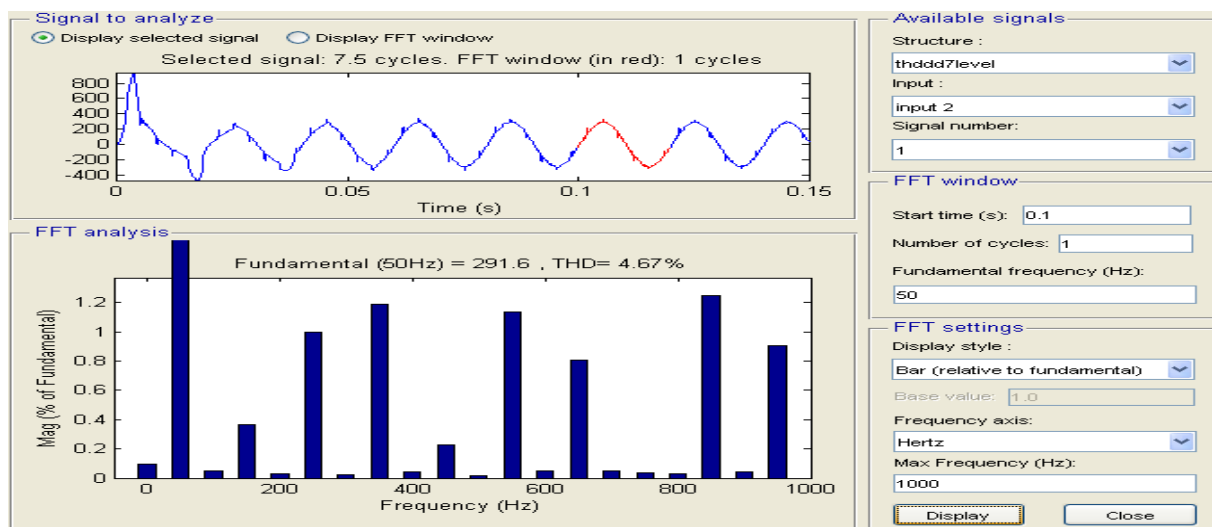


Figure 15: Harmonic spectrum of Phase-A Source current with Five level Active power filter

Figure15 shows the harmonic spectrum of Phase –A Source current with cascaded Multilevel Seven level active power filter. The THD of source current with seven level active filter is 4.37%.

V. CONCLUSION

A five-level and seven level cascaded multilevel voltage source inverter based active filter using instantaneous real-power controller is found to be an effective solution for power line conditioning. Shunt active filter with the proposed controller reduces harmonics and provides reactive power compensation due to non-linear load currents; as a result source current(s) become sinusoidal and unity power factor is also achieved under both transient and steady state conditions. The proposed instantaneous real-power controller uses reduced computation for reference current calculations compared to conventional approach. The cascaded inverter switching signals are generated using triangular-sampling current controller; it provides a dynamic performance under transient and steady state conditions. As evident from the simulation studies, dc bus capacitor voltage settles early and has minimal ripple because of the presence of PI-controller. The THD of the source current when five level active power filter is 7.34% after compensation is used Seven level active power filter 4.34% which is less than 5%, the harmonic limit imposed by the IEEE-519 standard.

Table III: System Specifications

S.No	System Parameters	Rating
1	voltage	11kv,50Hz
2	Inductance	0.9e-3h
3	Resistance	0.1ohm
4	Load	R=60,L=30e-3
5	Inverter Parameters	DC Link voltage=14kv

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