

# Cascaded H-Bridge Multilevel Inverter Based Shunt Active Power Filter

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**ABSTRACT:** The use of high voltage (HV) nonlinear load has increased considerably in industries nowadays. Hence, for HV systems the elimination of harmonics has become an important aspect. Use of Active Power Filter (APF) is the most popular technique because APF can easily eliminate unwanted harmonics, improve power factor and overcome voltage sags. In this paper, Multilevel Inverter (MLI) is used as APF in place of conventional Voltage Source Inverter (VSI). The use of MLI as APF in HV system eliminates the use of high cost transformer. The MLI based active power filter is analyzed through simulation study for different control methods like Instantaneous Reactive Power (p-q) method and Synchronous Reference Frame (d-q) method. Simulated results show the effective elimination of harmonics using Multilevel Inverter in high voltage system.

**KEYWORDS:** Multilevel Inverter (MLI), Active Power Filter (APF), Switching Signal Generation, Reference Current generation.

## I. INTRODUCTION

In recent years the use of power electronic converters and switching devices has widely increased at industrial and domestic levels. They act as nonlinear loads and draw highly nonlinear currents from the source or ac mains. They inject harmonics into the system which pollutes the power system and deteriorates the power quality by increasing the Total Harmonic Distortion (THD). Previously, in order to compensate for the load current harmonics L-C filters were used. But due to the disadvantages like bulky size, mistuning, instability, resonance with load or utility impedance and lack of flexibility, they needed to be replaced inherently [1-6] and viable solution for these problems is the use of Active Power Filters (APF). The shunt APFs act as a harmonic current source which injects an anti-phase but equal magnitude to the harmonic and reactive load current and hence eliminates the reactive and harmonic components of load current drawn from the utility.

The conventional Voltage Source Inverter (VSI) has limitation in medium and high voltage applications due to the power handling capabilities of the power semiconductor devices. In high voltage applications, multilevel inverters are increasingly used due to its direct high voltage output with no need of high cost transformer [2, 3].

In this paper, cascaded H-bridge multilevel inverter based shunt active power filter is presented. The simulated results for generation of reference currents are presented for two control methods, Instantaneous Reactive Power (p-q) method and Synchronous Reference Frame (d-q) method. The compensation of the load current using Cascaded MLI as Active Power Filter is presented for d-q technique. The generated current references are converted to voltage references using Forward Euler's Integration Algorithm. The gating signals for the MLI switches are generated using In-Phase Disposition (IPD) carrier based PWM technique.

## II. MULTILEVEL INVERTER BASED ACTIVE FILTER AND ITS CONTROL SCHEME

The cascaded H-bridge multilevel inverter has following advantages over diode clamped and flying capacitor multilevel inverters:

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- The circuit structure of each H-bridge is uniform which makes it easy to design.
- Each H-bridge has separate DC source which is easy to balance.
- In neutral point clamped (NPC) MLI and Flying Capacitor (FC) MLI, the number of diodes and capacitors increase with increasing the number of voltage levels leading to complicated control scheme.

Therefore, cascaded MLIs are preferred for harmonic mitigation without having voltage unbalance problem and there are no extra clamping diodes or voltage balancing capacitors[7]. The main drawback is the requirement of separate DC source for each H-bridge.

Fig-1 shows the three phase five-level MLI used as APF.  $I_{source}$  is the AC source current,  $I_{Load}$  is the load current, where three phase diode rectifier with R-L load is used as non-linear load.  $I_{compensated}$  is the compensated current from the APF. So,

$$I_{source} = I_{Load} + I_{compensated} \quad (1)$$

In the operation of APF, the harmonic component of the load current is detected using harmonic detection circuit and from that the reference compensation current is derived. The switching signals to the multilevel inverter are generated such that the output current of the inverter correctly traces the reference current and provides the harmonic current of the load. This causes the source current to be free from harmonics and approaches pure sinusoidal [3, 6, 7]. The APF will draw small power from the source to compensate the switching losses in the inverter.

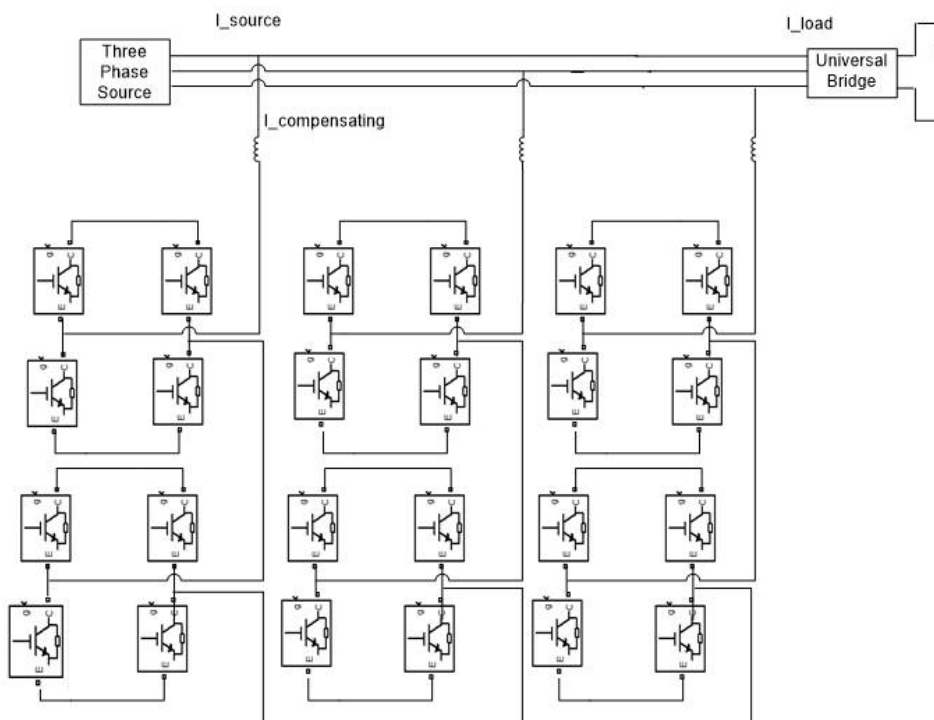


Fig-1 Cascaded H-bridge MLI based Active Power Filter

The performance of the active power filter relies on accurate reference generation. The reference generation technique is discussed in the following section.

## 2.1 REFERENCE CURRENT GENERATION USING P-Q THEORY

The p-q theory[12-15] defines a set of instantaneous powers in the time domain. There are no restrictions imposed on the voltage or current waveforms and they can be applied to the three-phase systems with or without neutral wire for

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the generic three-phase voltage and current waveforms. Thus, it is valid not only in the steady state, but also in the transient state. The p-q theory first transforms the voltages and currents from the abc to  $\alpha\beta$  co-ordinates and then the instantaneous power is calculated based on these co-ordinates. Thus, this theory considers three-phase system as a unit and not a superposition or sum of three single-phase circuits. The three phase voltages and currents are transformed into  $\alpha\beta$  co-ordinates as shown in Eq-(2) and (3).

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (3)$$

The instantaneous active and reactive power in  $\alpha\beta$  co-ordinates can be calculated by the following expressions

$$p_{(t)} = v_\alpha i_\alpha + v_\beta i_\beta \quad (4)$$

$$q_{(t)} = -v_\alpha i_\beta + v_\beta i_\alpha \quad (5)$$

The instantaneous real and reactive power consists of the dc and ac components. The dc component is the fundamental active power component and ac component is the harmonic component. Using low pass filter the fundamental active power component can be extracted and separated from the harmonic component.

The compensating currents in the  $\alpha\beta$  coordinates can be obtained as follows

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (6)$$

Then the reference currents can be obtained by transforming the coordinates from  $\alpha\beta$  to abc coordinates.

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \quad (7)$$

The advantage of this theory is that the fundamental components of the real and reactive powers are dc quantities. These quantities can be extracted using the low-pass filter. As the signals to be extracted are dc quantities and they are in  $\alpha\beta$  reference frame are insensitive to any phase shift errors introduced by the low-pass filter. This will enhance the compensation characteristics of the active power filter.

The limitation of this theory is that it requires pure sinusoidal supply voltages. In many industrial applications, the mains voltage is often unbalanced and distorted, in this case the p-q theory generate errors in the reference currents and limits the compensation of harmonics.

## 2.2 REFERENCE CURRENT GENERATION USING D-Q THEORY

In this method [16, 17], the voltage and/or current signals (abc) are firstly transformed to the orthogonal stationary frame ( $\alpha\beta$ ) using Clarke's Transform shown in Eq-(8) and then to synchronously rotating reference frame (d-q) frame using Park's Transformation shown in Eq-(9). In order to generate the reference signals and transform them back to original frame, the inverse transformation from d-q to  $\alpha\beta$  frame given by Eq-(10) and then to abc frame as shown in Eq-(7).

The transformation from abc to stationary ( $\alpha\beta$ ) reference frame using Clarke's Transformation

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (8)$$

Where, x represents the variable under consideration and can be voltage or current.

The transformation from  $\alpha\beta$  to synchronously rotating (d-q) reference frame

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \sin \omega t & -\cos \omega t \\ \cos \omega t & \sin \omega t \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \quad (9)$$

The inverse Park's transformation from d-q to  $\alpha\beta$  reference frame

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$$\begin{bmatrix} x_a^* \\ x_\beta^* \end{bmatrix} = \begin{bmatrix} \sin \omega t & \cos \omega t \\ -\cos \omega t & \sin \omega t \end{bmatrix} \begin{bmatrix} x_d \\ x_q \end{bmatrix} \quad (10)$$

The inverse Clarke's transformation from  $\alpha$ - $\beta$  to abc

$$\begin{bmatrix} x_a^* \\ x_b^* \\ x_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_\alpha^* \\ x_\beta^* \end{bmatrix} \quad (11)$$

One of the advantages of this method is that angle  $\theta$  is calculated directly from main voltages and thus makes this method frequency independent by avoiding the PLL in the control circuit. Consequently synchronizing problems with unbalanced and distorted conditions of main voltages are also evaded as the controller deals with mainly DC-quantities.

## 2.3 FORWARD EULER'S INTEGRATION ALGORITHM

The instantaneous reactive power (p-q) method [18] or synchronous reference frame (d-q) method gives us current references. For the MLI which is a voltage source inverter used as a SAPF, we need to convert these current references to voltage references in order to generate switching pulses using PWM technique. To achieve this Forward Euler's Integration algorithm is used. This method is based on the forward difference approximation. It can be written as

$$y_{n+1} = y_n + h f(x_n, y_n) \quad (12)$$

Where  $h$  is the step size,  $x_n$  and  $y_n$  is the input and output samples at  $n^{\text{th}}$  sampling instant respectively. The differential equation governing the relation between  $v_{ref}$  and  $i_c$  can be written as

$$\frac{di_c}{dt} = \frac{v_{ref} - v_{pcc} - R_i i_c}{L_i} \quad (13)$$

Where  $i_c$  is the current injected by the inverter at PCC.

By using the Forward Euler's formula given in (14), the differential equation (13) can be solved. The injected current is expected to follow the reference current. Hence, it is assumed that

$$i_{c(n+1)} = i_{ref(n)} \quad (14)$$

Hence, Eqn- (13) can be written as

$$i_{ref(n)} = i_{c(n)} + h \left[ \frac{v_{ref(n)} - v_{pcc(n)} - R_i i_{c(n)}}{L_i} \right] \quad (15)$$

On re-arranging the terms in Eqn-(15), the voltage reference can be obtained as follows

$$v_{ref(n)} = L_i \left( \frac{i_{ref(n)} - i_{c(n)}}{h} \right) + v_{pcc(n)} + R_i i_{c(n)} \quad (16)$$

Thus, the voltage references for all the three phases can be obtained using the Eq-(16).

These voltage references are then compared with the four triangular carrier waves using IPD modulation technique to generate gating signals for the MLI.

## III. SIMULATION RESULTS

The Cascaded H-Bridge MLI used as Shunt APF is simulated using MATLAB/Simulink. The nonlinear load considered for simulation study is the three phase uncontrolled converter with R-L elements on its DC side. The simulation parameters are mentioned as under:

AC Source Line Voltage = 110000 V, 50 Hz

Source Inductor = 0.5 mH

Source Resistance = 0.5  $\Omega$

AC side Filter Inductance = 5 mH

Carrier Frequency = 10 kHz

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The simulation results of MLI based shunt active power filter obtained using the d-q theory for reference generation is shown in Fig-2. The source voltage, load current  $I_L$ , filter current and current drawn from the source after compensation, for phase a are shown in Fig-2.

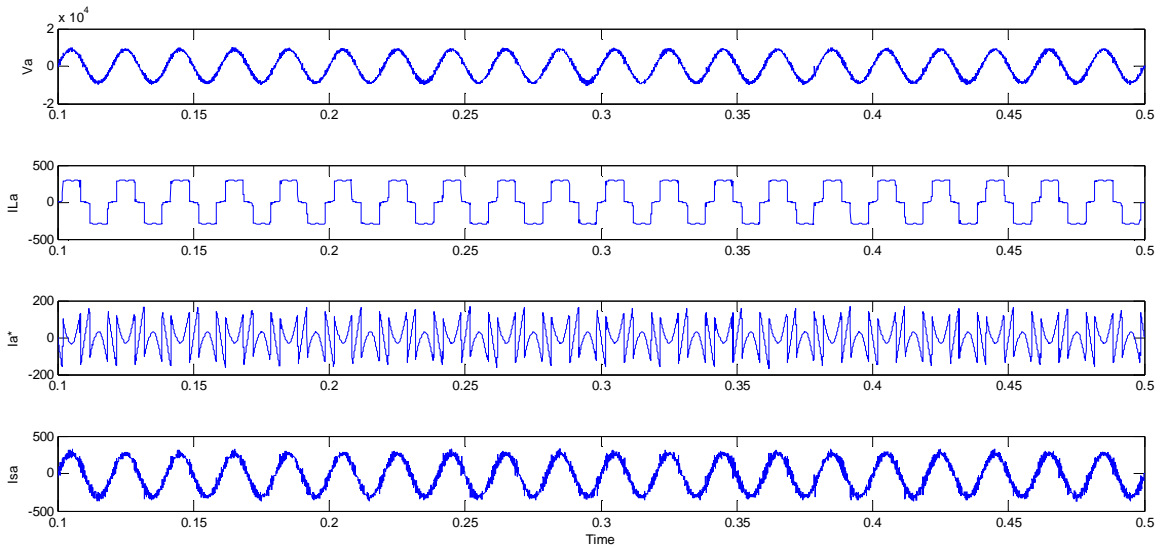
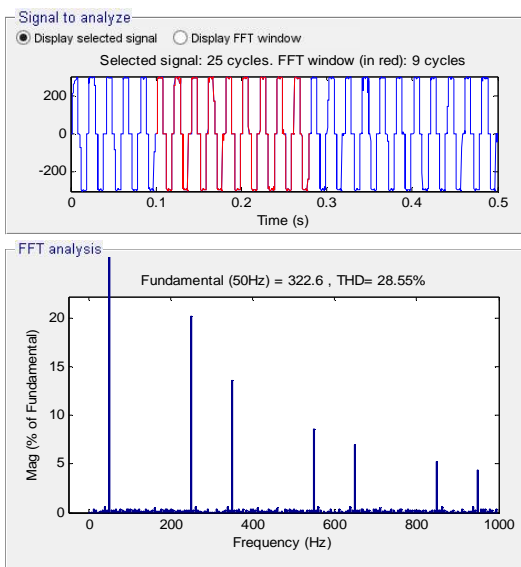
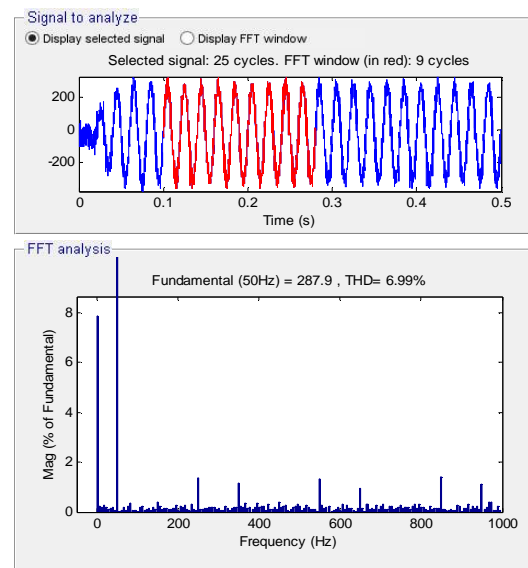


Fig-2 Simulation result of ideal mains voltage, load current, filter current and source current after compensation using d-q technique

The spectrum of load current is as shown in Fig-3(a) and the spectrum of source current after compensation is as shown in Fig-3(b). The THD of source current before compensation is 28.55% which is decreased to 6.99% after compensation by the MLI inverter as an APF.



(a) Spectrum of source current before compensation



(b) Spectrum of source current after compensation

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The simulated results of MLI based active power filter using the p-q theory for reference generation are shown in Fig-4. The voltage at PCC, load current  $I_L$ , filter current and source current after compensation for phase a are shown in Fig-4.

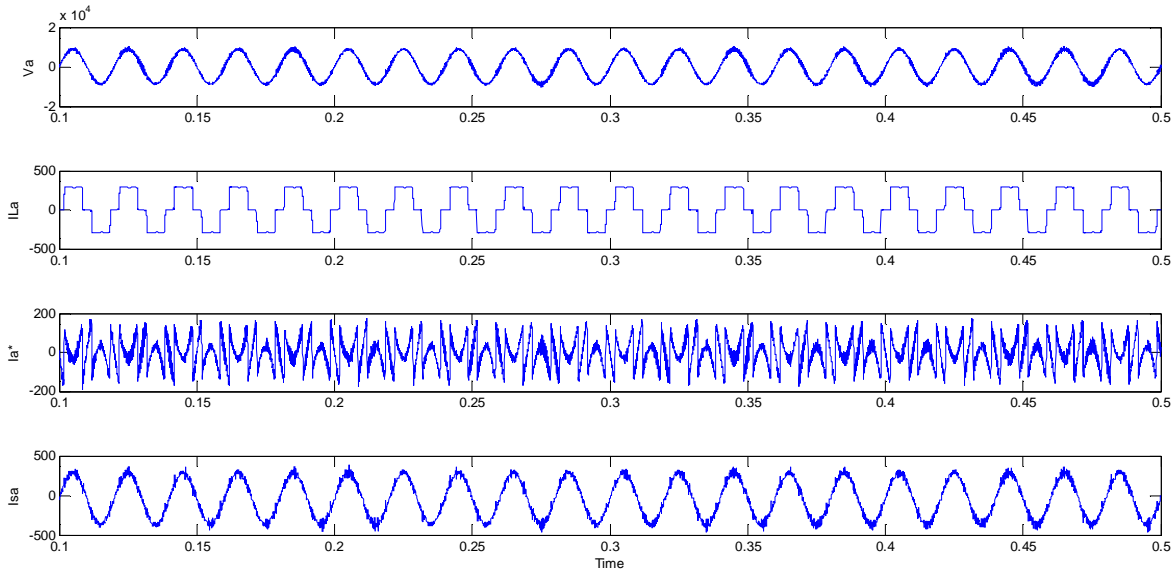
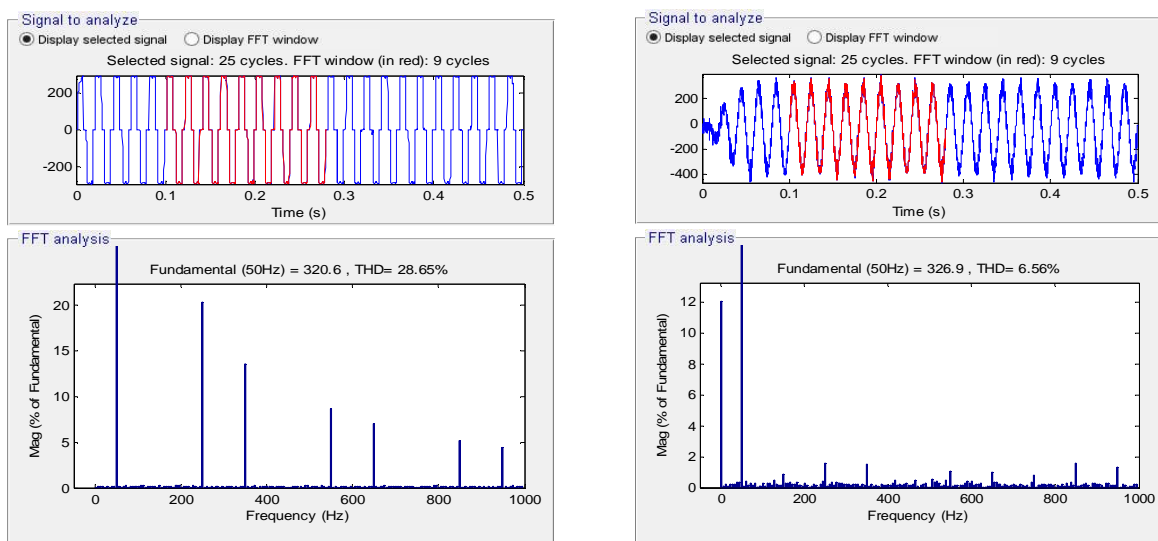


Fig-4 Simulation results of ideal mains voltage, load current, filter current and source current after compensation using p-q theory

The spectrum of load current is as shown in Fig-5(a) and the spectrum of source current after compensation is as shown in Fig-5(b). The THD of the source current before compensation is 28.65% that is reduced to 6.56% after compensation which shows that the MLI inverter acts as an APF.



(a) Spectrum of source current before compensation

(b) Spectrum of source current after compensation

Fig. 5 Spectrum of source current  $I_{sa}$  before and after compensation using p-q technique

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## IV. CONCLUSION

In this paper, simulation study of Cascaded H-Bridge MLI based Shunt APF is performed for high voltage system. The Cascaded H-bridge MLI based shunt active power filter eliminates the need of high cost transformer being used in high voltage systems. The In-Phase Disposition technique is used for the generation of gating signals of MLI because that gives lowest THD and also the individual device switching frequency is reduced. The simulation results are presented using d-q as well as p-q based reference generation. The simulation results show that the cascaded MLI based Shunt APF can compensate load current harmonics drawn from the source without the use of transformer in high voltage system and it works satisfactorily.

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