Harmonics Reduction using Multilevel Based Shunt Active Filter with SMES

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Abstract—**Nowadays, the increase in the usage of nonlinear loads leads to harmonics and waveform distortion to the power system. Shunt active filters (SAF) is commonly a voltage source inverter with the dc link capacitor which is used to mitigate the harmonics and voltage sag. In this paper, diode clamped multilevel inverter based shunt active filter has been designed and it injects the compensating current into system at the point of common coupling. A fuzzy logic controller is established to adjust the energy storage of the dc voltage. The instantaneous reactive power (p-q) theory is used to generate the reference current computation of the shunt APF. Hysteresis Controllers is used to generate switching signals of the voltage source inverter. Super conducting magnetic energy storage coil is capable of storing electric energy in the magnetic field generated by dc current flowing through it. Therefore the combined SAF and SMES system can be a perfect device to compensate both harmonic current and voltage sag. The proposed system is simulated using MATLAB/SIMULINK power system toolbox. Simulation results show that the leading harmonics are reduced considerably.**

Keywords- Fuzzy logic controller, Multilevel inverter, Nonlinear load, Shunt active filter, Superconducting Magnetic Energy Storage coil.

I. INTRODUCTION

The power quality (PQ) problems in power utility distribution systems are not new, but only recently their effects have gained public awareness. However the power electronics based equipment which include adjustable-speed motor drives, electronic power supplies, DC motor drives, battery chargers, electronic ballasts are responsible for the rise in PQ related problems. These nonlinear loads appear to be major sources of harmonic distortion in a power distribution system. Harmonic currents produced by nonlinear loads are injected back into power distribution systems through the point of common coupling (PCC).These harmonics are the origin of many problems and affect electrical equipment connected to the power supply. These harmonics induce malfunctions in sensitive equipment, Voltage stresses, increased heating in the conductors and harmonic voltage drop across the network impedance that affects power factor. Traditionally passive filters have been used to compensate harmonics and reactive power; but passive filters are large in size, aging and tuning problems exist and can resonate with the supply impedance.

Recently active power filters are designed for compensating the current-harmonics and reactive power simultaneously. The shunt APF based on Voltage Source Inverter (VSI) structure (a DC energy storage device in this case is capacitor) is an attractive solution to harmonic current problems. The shunt APF is designed to be connected in parallel with the nonlinear load. It detects the harmonic current of nonlinear load and injects into the system a compensating current, identical with the nonlinear load harmonic current but in opposite phase. Therefore, the net current drawn from the distribution network at the point of coupling of filter and the load will be a sinusoidal current of only fundamental frequency.

One of the important tasks in the shunt APF design is the maintenance of constant DC voltage across the capacitor connected to the inverter. This is necessary because there is energy loss due to conduction and switching power losses associated with the controllable switches of the inverter, which tend to reduce the value of voltage across the DC capacitor. Generally, PI controller is used to control the DC bus voltage. The PI controller based approach requires precise linear mathematical model which is difficult to obtain. Also, it fails to perform satisfactorily under parameter variations, non-linearity, and load disturbances. Recently, fuzzy logic controller has generated a great deal of Interest in various applications and has been introduced in the power electronics field. The advantages of fuzzy logic controllers over the conventional PI controller are that they do not need an accurate mathematical model; they can work with imprecise inputs, can handle nonlinearity, and may be more robust than the conventional PI controller. In the other hand, In APF design and control, p-q theory was often served as the basis for the calculation of compensation current. In this theory, the mains voltage was

assumed to be an ideal source in the calculation process. However, in most of time and most of industry power systems, mains voltage may be unbalanced and/or distorted; in this case the control using the p-q theory does not provide good performance.

This paper presents an analysis and simulation of a shunt APF topology that achieves simultaneously harmonic current damping and reactive power compensation under unbalanced mains voltages. To optimize the energy storage, a fuzzy logic controller is developed to adjust the energy storage of the dc voltage to its reference and to attenuate harmonic frequencies resulting from power fluctuations. For the reference current computation of the shunt APF, we used a new technique with p-q for the control of shunt APF. Hysteresis Controllers is used to generate switching signals of the voltage source inverter.

II. SHUNT ACTIVE FILTER STRATEGY

A. Shunt Active Filter

Shunt APFs have been the topic of interest for researchers as it compensates for current harmonics more effectively compared to traditional passive filters. It is barren of many drawbacks observed in passive filters such as, heavy weight, bulky size, harmonic resonance with power system impedance and ineffectiveness when harmonic content varies randomly. The APFs are designed to produce harmonics of equal magnitude and opposite phase as that present in load current. The filter generated harmonics are injected at the point of common coupling between the source and the load so as to cancel out the load current harmonics [3]. The switching loss occurring in two-level inverter based APF is not negligible, which in turn highly affects the performance of APF. Hence, an additional DC-link voltage regulator is required to maintain the DC-link capacitor voltage at a constant value. With the use of a multilevel inverter the switching losses are reduced by a large amount, as the switching occurs at fundamental frequency.

B. Diode-Clamped Multilevel Inverter

An m-level diode-clamped multilevel inverter typically consists of $(m − 1)$ capacitors and produces m levels of the phase voltage. A three-phase five-level structure of a DCMLI is shown in Figure 1. Each of the three phases of the inverter shares a common dc bus, which has been subdivided by four capacitors into five level s. The numbering order of the switches is S_{a1}, S_{a2}, S_{a3}, S_{a4}, S'_{a1}, S'_{a2}, S'_{a3} and S'_{a4}. The dc bus consists of four capacitors C_1, C_2, C_3, and C_4. For a dc bus voltage V_{dc}, the voltage across each capacitor is $V_{dc}/4$, and each device voltage stress is limited to one capacitor voltage level $V_{dc}/4$ through clamping diodes. An m-level inverter leg requires (m-1) capacitors, 2(m-1) switching devices and (m-1) (m-2) clamping diodes.
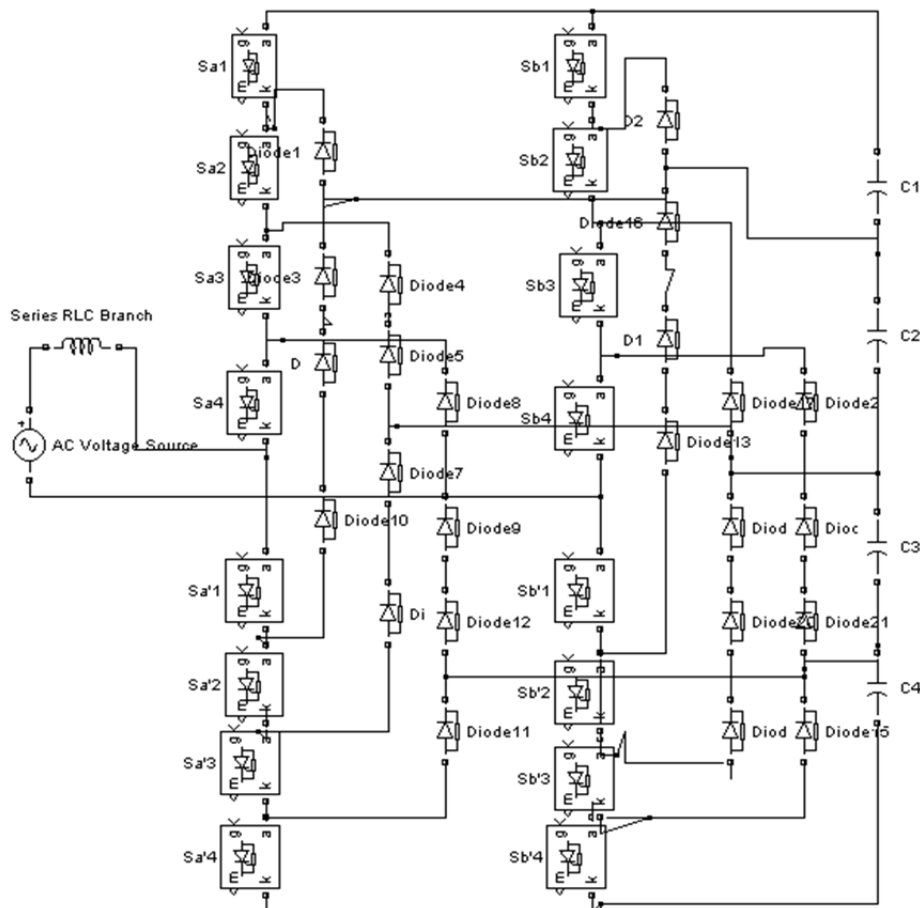
Fig 1.Diode-Clamped Multilevel Inverter

Table 1 shows the voltage levels and their corresponding switching states. State condition 1 means the switch is on, and 0 means the switch is off. Each phase has five complementary switch pairs such that turning on one of the switches of the pair require that the other complementary switch be turned off. The complementary switch pairs for phase are (*Sa1*, *Sa'1*), (*Sa2*, *Sa'2*), (*Sa3*, *Sa'3*), and (*Sa4, Sa'4*). Table I also shows that in a diode-clamped inverter, the switches that are on for a particular phase leg is always adjacent and in series [4]. Thus, if one of the complementary switch pairs is turned on, the other of the same pair must be off. Four switches are always turned on at the same time.

TABLE I

Diode-Clamped Voltage Levels and Their Switching State

Output V_{a0}	Switching State							
	S_{a1}	S_{a2}	S_{a3}	S_{a4}	S'_{a1}	S'_{a2}	S'_{a3}	S'_{a4}
$V_5 = V_{dc}$	1	1	1	1	0	0	0	0
$V_4 = 3\ V_{dc}/\ 4$	0	1	1	1	1	0	0	0
$V_3 = V_{dc}\ /\ 2$	0	0	1	1	1	1	0	0
$V_2 = V_{dc}/4$	0	0	0	1	1	1	1	0
$V_1 = 0$	0	0	0	0	1	1	1	1

III. HYSTERESIS CURRENT CONTROL TECHNIQUE

Hysteresis Current Control (HCC) technique is fundamentally an instantaneous feedback current control method of PWM, where the actual current constantly tracks the command current within a hysteresis band. Basic working principle of the HCC technique is shown in Figure 2. Hysteresis band (HB) is the potential boundary of the compensating current [13]. This current departs between upper and lower hysteresis limits. For example in phase *a*, if I_f is equal or over than the upper hysteresis limit (I_f* + HB/2) then the comparator output is 0 (g1=0, g2=1). On the other hand, if I_{fa} is equal or less than the lower hysteresis limit (I_{fa}* - HB/2) then the comparator output is 1 (g1=0, g2=1).
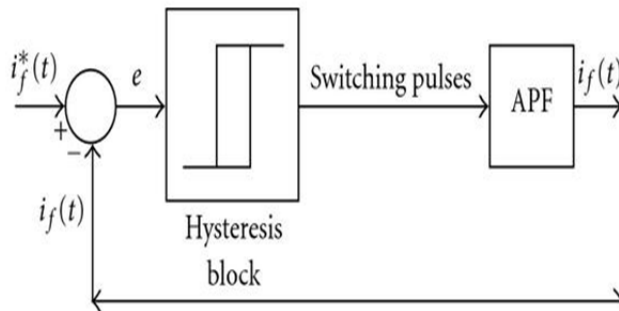

Fig 2. Working Principle of the HCC Technique

IV. INSTANTANEOUS REACTIVE POWER THEORY

The *p-q* theory is based on transformation of *a-b-c* coordinate into *α-β-0* coordinates and *α-β-0* coordinates into *a-b-c* coordinates, popularly known as Clark transformation and inverse transformation respectively [7]. Simple block diagram of *p-q* theory is shown in Figure 3. Generated compensating current will be:

$$I_{comp} = I_{source} - I_{load} \qquad (1)$$

Where,

I_{comp} = Compensating current
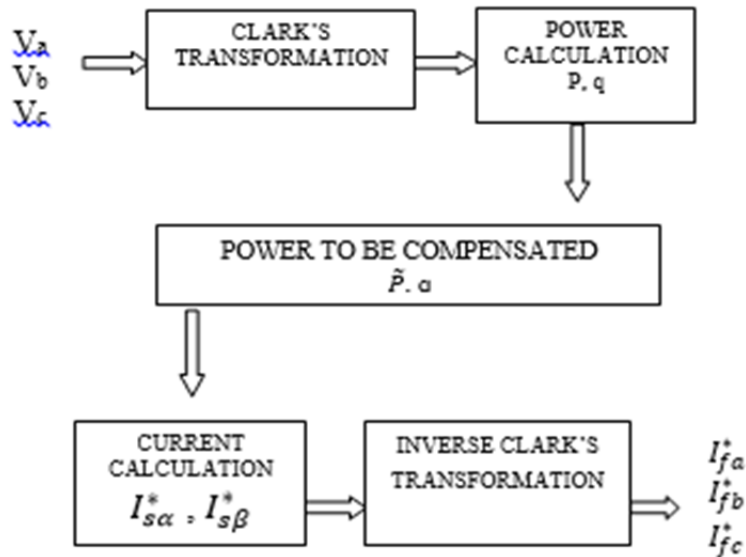I_{source} = Source current and
I_{load} = Load Current

Fig 3. Basic Block Diagram of P-Q Theory

.In this method three phase source voltage and load current are converted into α-β-0 stationary reference frame

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & 1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \qquad (2)$$

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & 1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} \qquad (3)$$

From this transformed quantities, instantaneous real and reactive power of the load is calculated which consists of average and oscillating component.

$$\begin{bmatrix} P_0 \\ P \\ q \end{bmatrix} = \begin{bmatrix} V_0 & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} \qquad (4)$$

For three phase three wire systems $I_0 = 0$, so source power P_0 also becomes zero. So power equation becomes as follows.

$$\begin{bmatrix} P \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \qquad (5)$$

Instantaneous active and reactive power of load can be calculated as follows:

$$\begin{bmatrix} P_l \\ q_l \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_{l\alpha} \\ I_{l\beta} \end{bmatrix} \qquad (6)$$

Instantaneous real and reactive power can be moldy into two components called oscillatory components and average components.

$$\begin{bmatrix} I_{s\alpha} \\ I_{s\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} P \\ 0 \end{bmatrix} \qquad (7)$$

The oscillating component is extracted by high-pass filter and taking inverse of α-β transformation compensating reference signals in terms of either currents or voltages are derived.

$$\begin{bmatrix} I_{fa}^* \\ I_{fb}^* \\ I_{fc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I_{s\alpha} \\ I_{s\beta} \end{bmatrix} \qquad (8)$$

The reference currents in three-phase system (I_{fa}^*, I_{fb}^* and I_{fc}^*) are calculated so as to compensate harmonic currents in the load. The switching pulses used in shunt active power filter control algorithm are created by comparing reference currents and actual line currents by hysteresis band current control algorithm.

V. Fuzzy Logic Controller

Fuzzy logic is a form of many -valued logic that deals with approximate, rather than fixed and exact reasoning. Compared to traditional binary logic, fuzzy logic variables may have a truth value that ranges in degree between 0 and 1. Fuzzy logic has been extended to handle the concept of partial truth, where the truth value may range between completely false. Now-a-days, fuzzy logic controller is used in almost all sectors of industry power systems and science [5]. One of them is the harmonic current and reactive power compensation control.

A fuzzy inference process consists of the following steps:

Step 1: Fuzzification of input variables
Step 2: Application of fuzzy operator (AND, OR, NOT) in theIF (antecedent) part of the rule
Step 3: Implication from the antecedent to the consequent (THEN part of the rules)

Step 4: Aggregation of the consequents across the rules
Step 5: Defuzzification

The crisp inputs are converted to linguistic variables in fuzzification based on membership function (MF). A membership function can have different shapes.

A.   DC Capacitor Voltage Control

Among the various available powers filter controllers PI, PID, RST hysteresis and fuzzy logic controller. In this application, the fuzzy control algorithm is implemented to optimize the energy storage of the DC capacitor voltage based on DC voltage error E (t) processing and its variation E (t) in order to improve the dynamic performance of APF and reduce the total harmonic source current distortion [5]. Fuzzy logic uses linguistic variables instead of numerical variables. In a control system, error signal E, its variation ΔE and output signal DΔE can be assigned as negative Large: (NL); negative medium :(NM); negative small :(NS); zero: (ZE); positive small: (PS); positive medium: (PM) and positive Large: (PL). The process of fuzzification convert numerical variable (real number) to a linguistic variable (fuzzy number).

TABLE II

Fuzzy Control Rules

ΔE \ E	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	NL	NM	NS	ZE	PS	PM	PL

VI. SMES

A variety of storage tools are in the market but the most feasible is superconducting magnetic energy storage systems. The drawbacks of other methods are restricted life cycle, voltage and current limitations, and potential environmental hazards. SMES is a large superconducting coil capable of storing electric energy in the magnetic field generated by dc current flowing through it. Figure 4 shows the basic block diagram of SMES coil [15]. The real power as well as the reactive power can be absorbed by or released from the SMES coil according to system power requirements. Although superconductivity was discovered in 1911, SMES has been under study for electric utility energy storage application since the early 1970s [6].
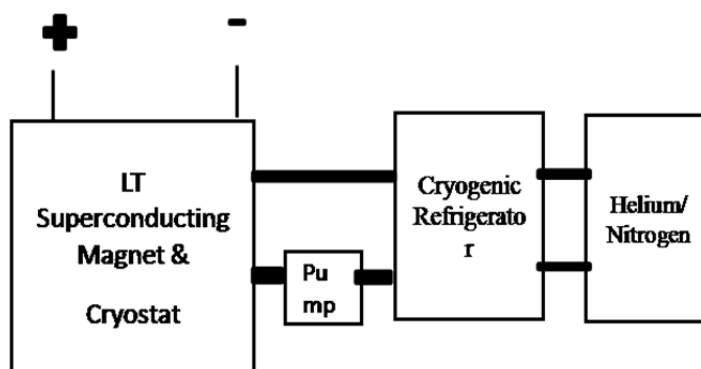

Fig 4. Block Diagram of SMES coil

A. Application of SMES in Power Systems

It is the fast response that makes SMES able to provide benefit to many potential utility applications. The applications of SMES are;

- Energy storage range of SMES is up to 5000MWh with a high return efficiency (up to 95% for a large unit) and a fast response time for dynamic change of energy flow.
- SMES has the ability to damp out the low power oscillations and stabilize the system frequency.
- SMES is useful in reducing dynamic voltage instability by supplying real and reactive power simultaneously.
- SMES can be used as a backup power supply for large industrial customers in case of loss of the utility main power supply.
- SMES unit can represent a terrific amount of spinning reserve capacity when in charge mode.

VII. PROPOSED SYSTEM

This paper propose the control strategy for mitigating the harmonics and voltage sag problem in the power systems using the combined co-ordination of multilevel based shunt active filter and SMES. The block diagram of the system is shown in Figure 5. Three phase source is given to the nonlinear load. The nonlinear load used here is the diode bridge rectifier with the resistance of 10Ω. The diode clamped multilevel inverter is used in this model.
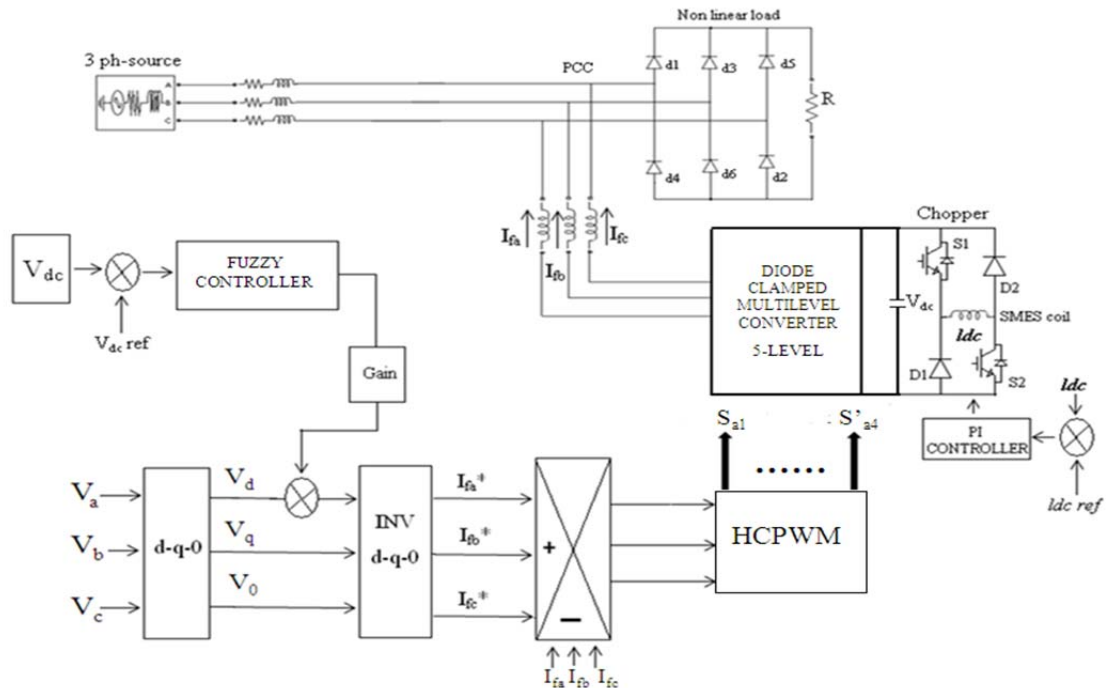

Fig 5. Three Phase Shunt Active Power Filter.

VIII. SIMULATION RESULTS

The proposed system considered in this paper is simulated using the MATLAB/Simulink Sim power system toolbox. The simulation results are based on the presence of SMES coil. Figure 6 shows the three phase voltage source.
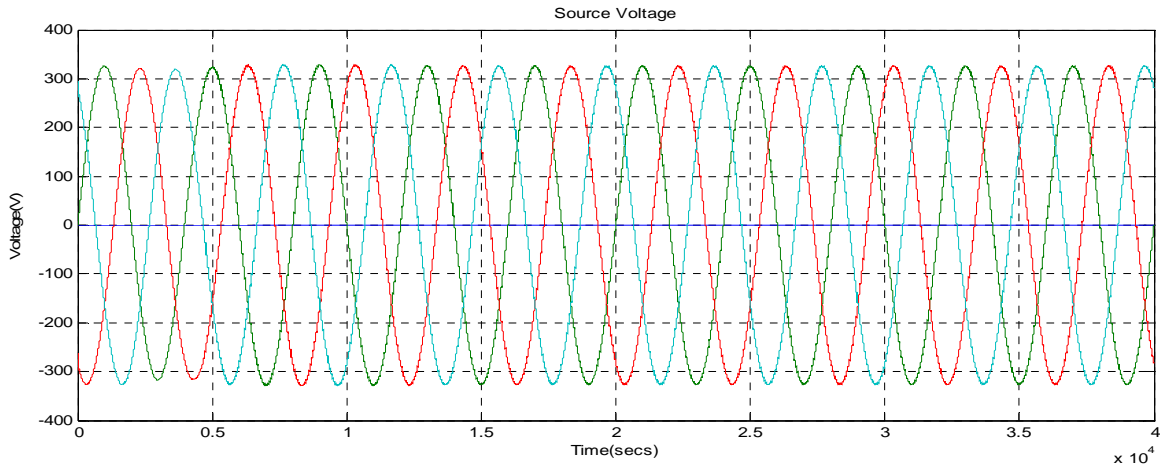
Fig 6. Three Phase Source Voltage

The nonlinear load considered in this paper is diode bridge rectifier with the resistor. Diodes are the source to produce this type of harmonic current as shown in Figure 7.
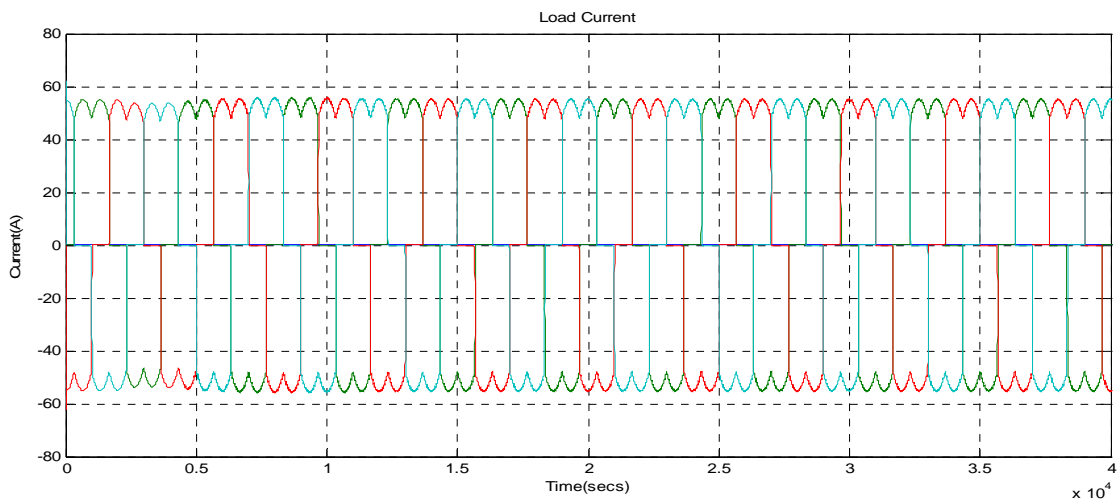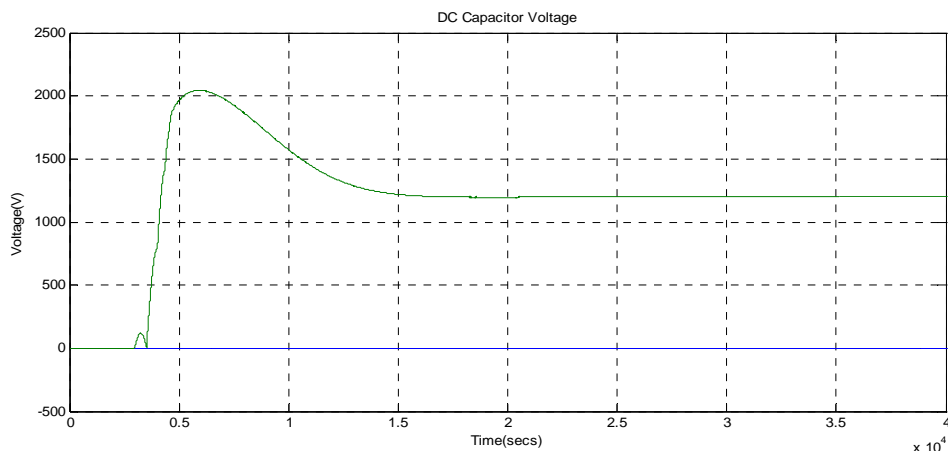

Fig 7. Three Phase Nonlinear Load Current

Fig 8. DC Capacitor Voltage

The main aim is to maintain the dc link voltage as constant and load current as sinusoidal. This achieved through fuzzy logic controller unit; in this error value and change in error value of load current is measured and compared with each other. Based on this result control signal is generated from the filter circuit to the load. The Figure 8 shows the DC capacitor voltage. V_{dc} is kept constant as 1200V.
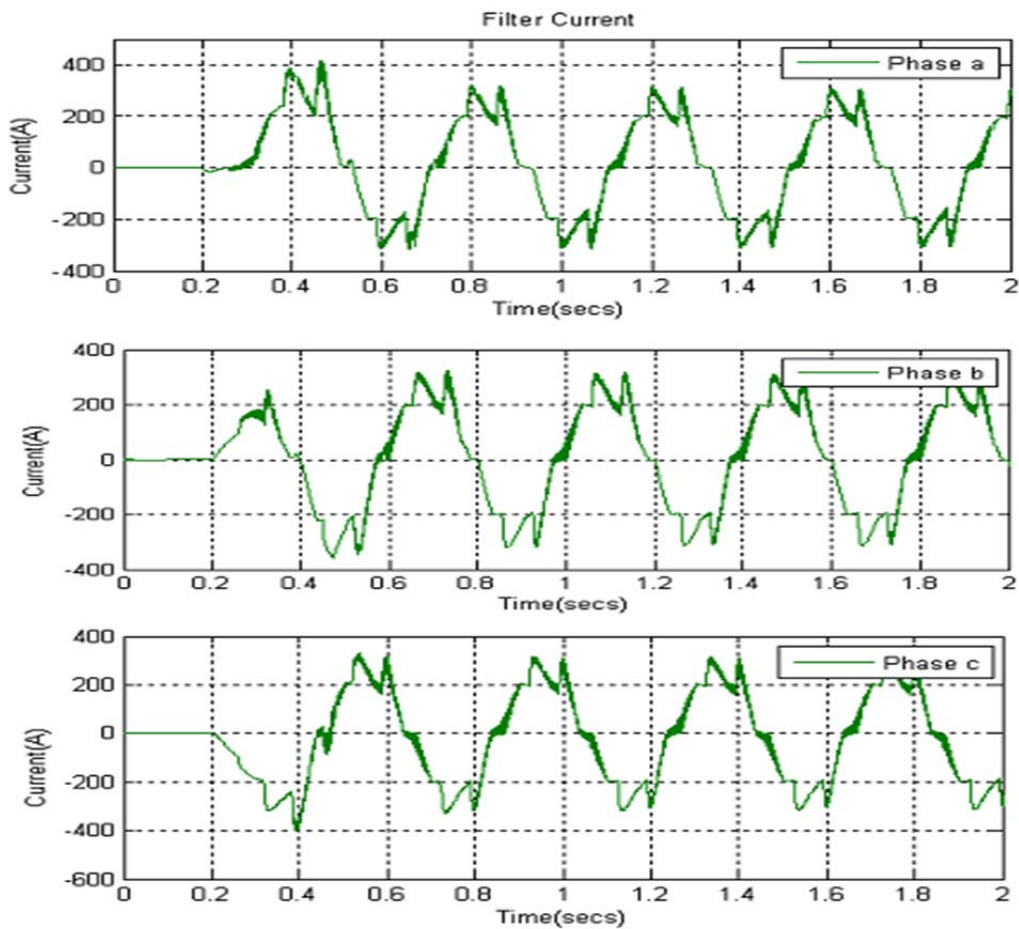

Fig 9. Three Phase Filter Current

Figure 9 shows the filter current waveform. This is due to the presence of 5 level diode clamped multilevel inverter. Three phases a, b, c are shown separately. This current is going to be injected at the point of common coupling. SMES is used as an additional energy source along with the capacitor. Figure 10 shows the compensated filter current. After some distortion, the source current is gradually compensated. Figure 11 shows the Harmonic Spectrum of Load Current, Source Current and DC Capacitor Voltage
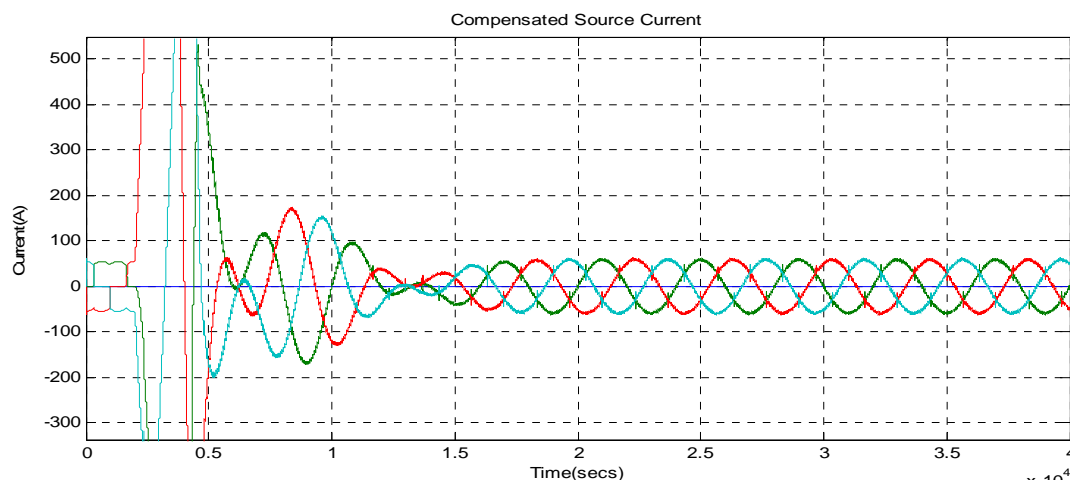
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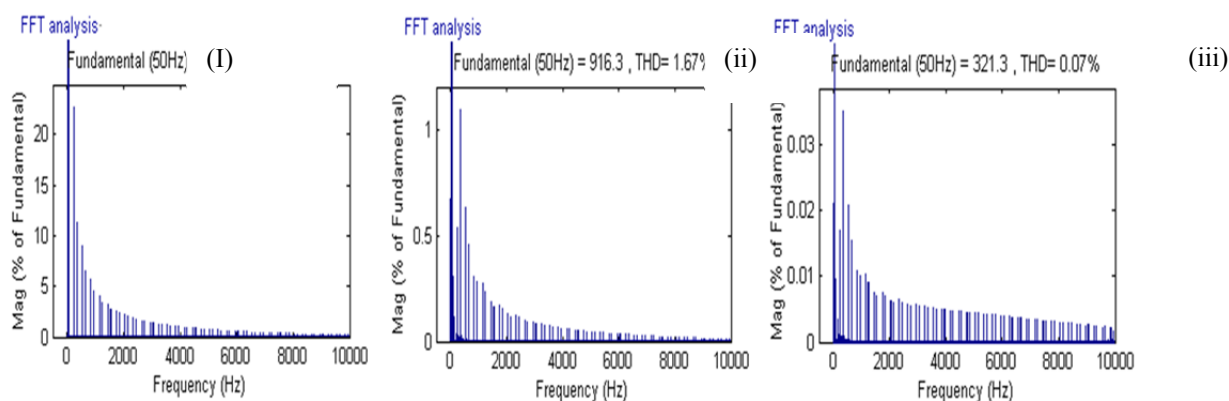

Fig 10. Compensated Source Current

Fig 11. Harmonic Spectrum of (i) Load Current (ii) Source Current (iii) DC Capacitor Voltage

IX. CONCLUSION

This paper has discussed the control and performance improvement of a shunt APF under distorted voltage conditions, using a fuzzy logic controller for a five level shunt APF based on the optimization of the reference current generation and using a modified version of the p-q theory and HCPWM to generate switching signals. Simulation results have shown high performances in reducing harmonics. The use of the SAF leads to satisfactory improvements since it perfectly extracts the harmonic currents under distorted conditions. In addition, the results have demonstrated the major advantages of using SAF and fuzzy logic controller in filter control. The five-level APF provides numerous advantages such as improvement of supply current waveform, less harmonic distortion and possibilities to use it in high power applications. As a final conclusion, the source current total harmonic distortion (THD) after compensation by single inverter is 3.73% but by using two inverters it decreases to 1.67% which is agreed and less than the harmonic limit imposed by the IEEE-519 standard (3%), by using multilevel inverters with 5-Step diode clamped multi-level inverter the circuit is simulated by using MATLAB/ Simulink.

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