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Fuzzy Controlled Multilevel Inverter Based Shunt Active Power Filter for Harmonics Reduction

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ABSTRACT

This paper presents a five-level cascaded multilevel inverter based Shunt Active Power Filter (SAPF) to compensate reactive power and mitigate the harmonic currents generated by the non-linear loads. The control strategy of SAPF incorporates Synchronous Reference Frame (SRF) theory to extract the harmonic components from distorted line currents which in turn are utilized in the production of required reference compensation currents, Fuzzy logic controller for dc-side voltage regulation of SAPF and multi carrier PWM current controller for the generation of switching pulses for the inverter switches. Extensive simulations are carried out to validate performance of the proposed SAPF system using MATLAB/ SIMULINK for diode bridge rectifier with RL load. To improve the performance of SAPF, a novel control strategy using Fuzzy Logic Controller (FLC) is proposed which eliminates the drawback of using fixed gains in conventional PI controller. From the simulation results the proposed fuzzy controlled Multi Level Inverter based SAPF provides effective and efficient mitigation of harmonics.

Keywords : Cascaded H-Bridge Multilevel Inverter (CHBMLI), Shunt Active Power Filters (SAPFs), synchronous reference frame (SRF) theory, multi carrier PWM, harmonic current compensation.

I. INTRODUCTION

Increased use of power electronics appliances in industrial, commercial and domestic applications results in rapid variation of reactive power and augmented deterioration of the power systems voltage and current waveforms. The introduction of harmonics in the utility system leads to greater power losses in distribution networks, overloading, overheating and failure of power factor correction capacitors.

Owing to these problems, the issue of power quality delivered to the end customers is becoming a thing of serious concern. International standards concerning electrical power quality put forth that electrical equipments and facilities should not produce harmonic currents greater than the specified values and also specify the distortion limits to the supply voltage. Traditionally shunt passive filters, which consists of tuned LC filters are employed to improve power factor and to suppress unwanted harmonics in power systems. There are certain factors which discourage the use of passive filters such as

- Harmonic amplification at specific frequency.
- Component ageing.
- Fixed compensation for specific loads.
- The shunt passive filter which acts as a sink to the harmonic current flowing from the source falls in series resonance with the source impedance.

To overcome the above disadvantages, currently Active Power Filters (APFs) are identified as an appropriate solution for power quality problems. There are several topologies of active power filters for harmonic mitigation such as series, shunt, series-shunt type (unified power quality conditioner) and hybrid configurations. The series active power filters are employed for voltage harmonic compensation. The necessity of current harmonic compensation in many industrial applications paved the popularity of shunt APFs than series active filters. Voltage Source Inverters (VSI) is an attractive solution to harmonic current problems. Due to the power handling capabilities of power semiconductors, these two-level inverters are limited for low power applications.

The harmonic reduction in output waveform without increasing switching frequency or decreasing the inverter power output makes Multi Level Inverters (MLIs) as an ideal suggestion for the power circuit topology of SAPF. A multilevel inverter with m-levels can increase the capacity by (m-1) times than that of two-level inverters through the series connection of power semiconductor devices without additional circuit to have uniform voltage sharing.

There are three well known topologies of MLIs: Neutral Point Clamped (NPC) MLI, Flying Capacitor (FC) MLI and the Cascaded H-Bridge MLI (CHBMLI). The first generation of MLI called NPC multilevel inverter, also called diode-clamped, was introduced by Nabae which was a three-level inverter. However, the number of diodes and capacitors increases with increasing the number of voltage levels leading to complicated control scheme. Cascaded MLIs are preferred for harmonic mitigation without having voltage unbalance problem and there are no extra clamping diodes or voltage balancing capacitors. In this work, 5-level CHBMLI has been used as the shunt active power filter for harmonic suppression.

To put shunt APF in effective use, it is essential to adopt a suitable control strategy for the extraction of reference compensation currents. Instantaneous active and reactive power theory (p-q theory), SRF Theory are some of the control strategies for reference current extraction in active power filters. H. Akagi put forth p-q theory which is quite efficient method for balanced three phase loads but this method requires a number of calculations, complex mathematical transformations and suffers from synchronization problems. In 1995, Bhattacharya proposed the calculation of d-q components called Synchronous Reference Frame (SRF) theory which is concise and yields good dynamic performance.

The energy loss due to conduction and switching power losses associated with the diodes and MOSFETs of the inverter in APF tend to reduce the value of dc voltage across the dc capacitor. Thus, the maintenance of constant dc voltage across the capacitor connected to the inverter is another important aspect to be considered in the development of active filters. In this work, SRF theory which incorporates Fuzzy Controller for dc voltage regulation of SAPF is used as an efficient control strategy for reference current extraction of the SAPF. There are various PWM current control strategies for shunt active power filter. In this work, the switching pulses for the cascaded inverter switches are generated using Level Shifting PWM current controller. Paper is organized in five sections starting from introduction, the subsequent sections cover configuration of SAPF, the control strategies for SAPF, simulation results of the proposed system and the conclusion.

II. SHUNT ACTIVE FILTER

A. **Principle**

The shunt active power filter behaves as a current source injecting the harmonic components generated by the load which are equal but phase shifted by 1800, which forms the basic principle of SAPF. As a result, components of harmonic currents in the load are cancelled by the effect of shunt active power filter and the source current remains sinusoidal and in phase with the respective voltage. The complete diagrammatic representation of CHBMLI based shunt active power filter is shown in Fig.1. The three phase source is connected to diode rectifier (non-linear) load. The SAPF is realized with 5-level CHBMLI consisting of 24 IGBTs/Diodes, a dc-side capacitor and RL filter (RF, LF) which suppresses the harmonics caused by the switching operation of the IGBT inverter.

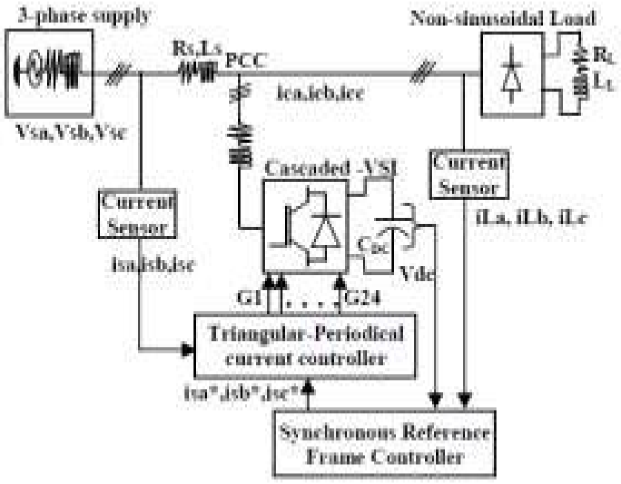

Figure 1. Principle of proposed SAPF system

The control scheme consists of Fuzzy logic controller for DC voltage regulation, SRF theory for reference current generation and the TCC to spawn the switching pulses for driving switches in the MLI.

B. 5-Level Cascaded H-Bridge Multilevel Inverter

A 3-phase, 5-level Cascaded H-Bridge Multilevel Inverter (CHBMLI) depicted in Fig.2 is used as the power circuit for shunt active power filter in this work. This inverter requires two, two-leg, series connected H-bridges and four triangular carrier waves. Fig.2 shows two H-bridges connected to a single phase consisting of two parallel legs which has two MOSFETs as a switching device, in a single leg. For a 5-level MLI, m=5, where m is the number of levels in MLI, four carrier waves are required.

The output of the current controller are applied as gating pulses for the inverter switches. The triangular carrier current controller is put in use as it has uniform switching stress for each phase. The MLI has two series connected H-bridges per phase with Vdci1 and Vdci2 as two voltages to be regulated, where i corresponds to the three phases (a,b,c) of the inverter. The number of output voltage levels of CHBMLI is given by 2n+1, where n is the number of H-bridges connected in cascade.

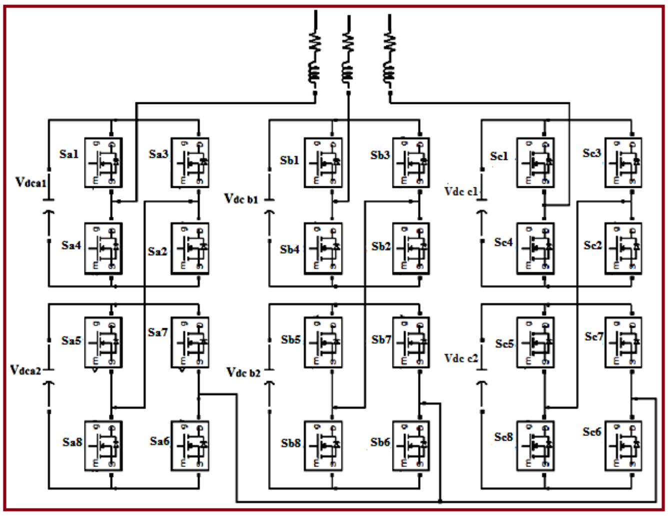

Figure 2. 5-level, Cascaded H-Bridge Multilevel Inverter

III. CONTROL STRATEGIES

A. Reference current extraction

In this work, the time domain based synchronous reference frame theory is utilized to extract the reference current from the distorted line current. Fig.3 shows the basic block diagram of SRF theory consisting of PLL circuit for the generation of unit vectors (sinθ and cosθ) and a controller for dc-side capacitor voltage regulation.

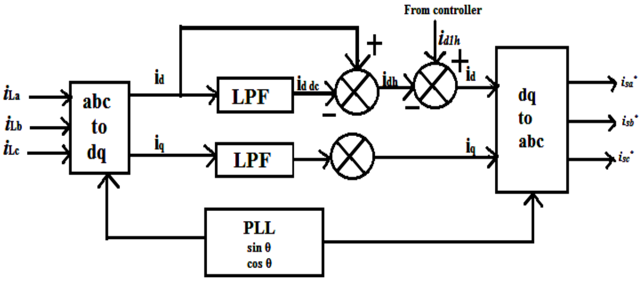

Figure 3. Block diagram of SRF theory

In this method, the three phase line currents i_{La} , i_{Lb}, $i_{Lc}$are first detected and transformed into two-phase synchronous (or rotating) frame (d-q axes) using park's transformation as given in Eqn.1.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\theta & \sin\left(\theta-\frac{2\pi}{3}\right) & \sin\left(\theta+\frac{2\pi}{3}\right) \\ \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \end{bmatrix}\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad ....1$$

The reference frame is rotating synchronously with fundamental currents. This results in time variant currents with fundamental frequencies which are constant after transformation. Each current component $(id\,, iq)$ has an average value or dc component and an oscillating value or ac component as shown in Eqn.2.

$$\boldsymbol{i_d = \bar{i}_d + \tilde{i}'_d} \qquad \text{....2}$$

The i_d and i_q currents obtained from park transformation are passed through a Butterworth type low pass filter to eliminate dc components in the non-linear load currents. To minimize the inverter losses, the required current is added to the positive sequence fundamental frequency active component of the d-q current. Now the currents from two phase synchronous frame are transformed back into three-phase stationary (a-b-c) frame using inverse Park's transformation as per Eqn.3 and the required reference currents are obtained.

$$\begin{bmatrix} \boldsymbol{i^*_{sa}} \\ \boldsymbol{i^*_{sb}} \\ \boldsymbol{i^*_{sc}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{sin\theta} & \boldsymbol{cos\theta} \\ \boldsymbol{\sin\left(\theta - \frac{2\pi}{3}\right)} & \boldsymbol{\cos\left(\theta - \frac{2\pi}{3}\right)} \\ \boldsymbol{\sin\left(\theta + \frac{2\pi}{3}\right)} & \boldsymbol{\cos\left(\theta + \frac{2\pi}{3}\right)} \end{bmatrix} \begin{bmatrix} \boldsymbol{i_d} \\ \boldsymbol{i_q} \end{bmatrix}$$

….3

The obtained reference signals ($\boldsymbol{i^*_{sa}}$, $\boldsymbol{i^*_{sb}}$, $\boldsymbol{i^*_{sc}}$) are compared with the actual load currents in a comparator and the output which acts as the reference signal for triangular carrier current controller. This consequently provides gating signals to trigger the switches of the MLI.

B. Triangular carrier PWM current controller

Most of the current control techniques used for APF are based on PWM-current control strategy. However, the high performance of the current-control is a difficult task in most practical cases, where the inverter load is unidentified and changeable. For the efficient performance of the SAPF, it is essential that the system must supply current in response to the generated reference current. In this work, triangular carrier current controller has been used for the generation of current pulses for the switches of CHBMLI. The reference currents are compared with the actual load currents. This error current is used as the modulating signal and is compared with the four carrier signals in the TCC to produce necessary gating signals for the inverter switches. Fig. 5.8 shows the current control scheme using TCC for phase 'a' of the CHBMLI.

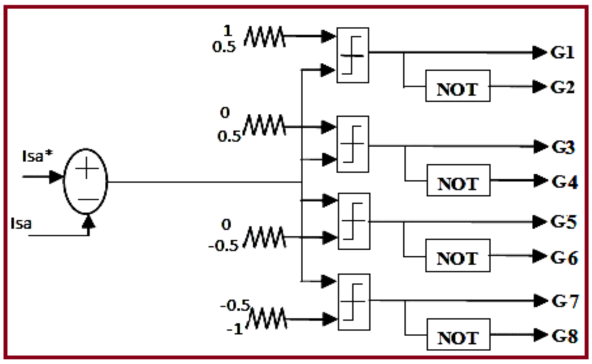

Figure 4. Current pulse generation for phase 'a' using TCC

C. *DC link voltage regulation*

For the APF to work properly, it is essential that the capacitor voltage at the dc-link must remain constant. For this purpose the active power flowing into the active filter needs to be monitored. The dc-link voltage can be maintained at the desired value, if the active power flowing into the filter can be controlled equal to the losses inside the filter. In view of practical implementation, dc-link voltage fluctuations may result from commutation, conductance and own-capacitor losses plus control system delays. The filter operates as a controlled rectifier thereby transferring a little amount of active power from the ac to the dc side of the inverter, for compensating the voltage variations. In order to maintain dc link voltage constant and to generate the compensating reference currents, fuzzy logic controller is used in this work.

Fuzzy logic controller for DC voltage regulation

Fuzzy logic unlike Boolean or crisp logic, deal with problems that have vagueness, uncertainty or imprecision and uses membership functions with values varying between 0 and 1. It has been proven to be an excellent choice for many control system applications since it mimics human control logic. The power loss for the APF is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through Fuzzy Logic Controller (FLC), which contributes to nearly zero steady error in tracking the reference current signal. Fuzzy Sets are chosen based on the error in the dc link voltage. We have considered 7x7 membership function. For the flexibility of program {NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium) and PB (positive big)} are used. These seven membership functions are same for input and output. The Membership Function used for the Fuzzy Interference System (FIS) is given in fig.5 and fig 6 below.

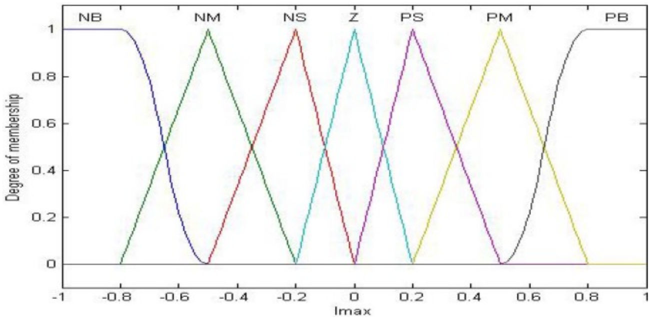

Figure 5..Membership Function for Input Error(e) and rate of change of error.

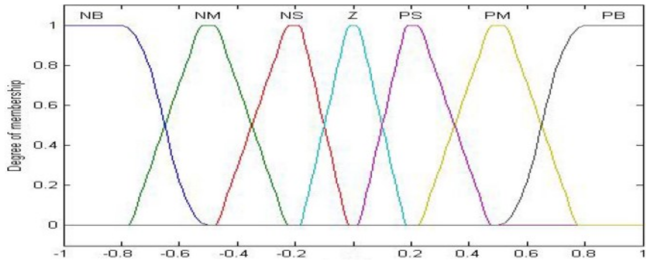

Figure 6. Membership Function for the Output as current

In a FLC a rule base is constructed to control the output variable. A Fuzzy rule is a simple IF-THEN rule with a condition and a conclusion. The Fuzzy control rule design involves defining rules that relate the input variables to the output model properties. In the case of the fuzzy logic based DC voltage control, the capacitor voltage deviation and its derivative are considered as the inputs of the FLC and the active current for real power (P.reg) requirement for the voltage regulation is taken as the output of the FLC. The input and output variables are converted into linguistic variables. Control rule table is shown below.

TABLE I : CONTROL RULE TABLE

ΔError/Error	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PM	NS	Z	PS	PM	PB	PB	PB
PS	Z	PS	PM	PB	PB	PB	PB

IV. SIMULATION RESULTS

The proposed technique is implemented in MATLAB/SIMULINK working platform to validate the performance of the system using fuzzy controller. The effectiveness of fuzzy logic controller is proved in terms of THD minimization of source currents before and after compensation.The simulation time is taken as 50 µs and the proposed system is simulated for 0.5s. Here, three phase diode rectifier with RL load is taken as the non-linear load.

A. Simulation results for uncompensated system

Fig.7 shows the source current waveforms before compensation with the SAPF. The corresponding harmonic spectrum is shown in Fig. 8.

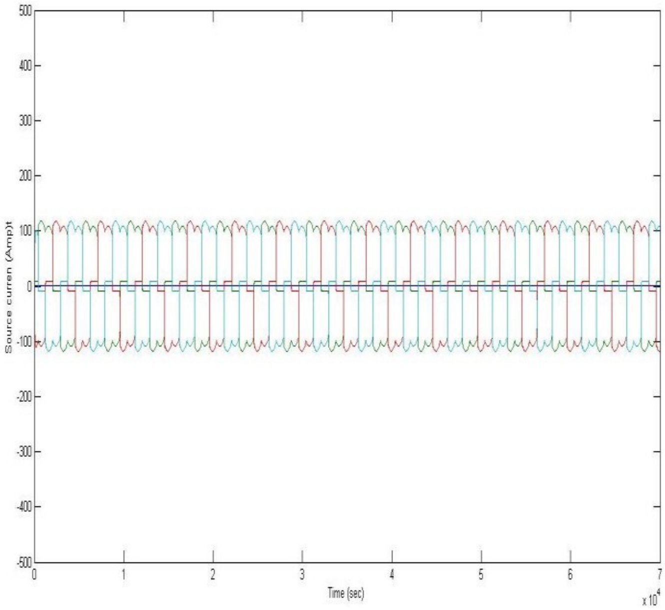

Figure 7. Source current before Compensation

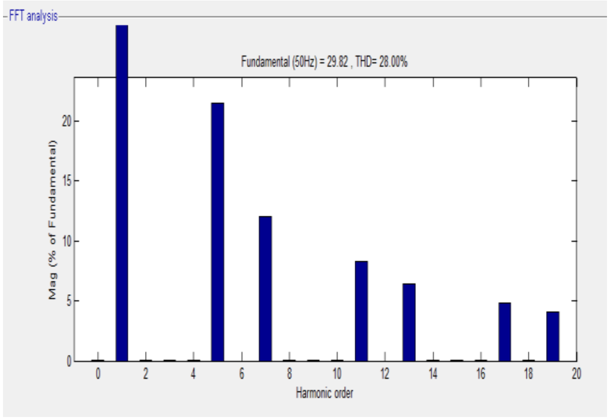

Figure 8. Source current spectrum for uncompensated system

B. Simulation results with fuzzy logic controller

The system parameters for simulation are given in Table II. The Simulation model of the Proposed CHB MLI Based Shunt Active Filter with Fuzzy Logic Controller is shown in Fig 9. Waveforms of source current and injected current after APF application with fuzzy controller are given in Figs. 10 and 11 respectively.

TABLE II SYSTEM PARAMETERS FOR SIMULATION

System Parameters	**Values**
Phase-phase source rms voltage	440 V
System frequency	50 Hz
Source resistor (Rs)	1 Ω
Source inductor (Ls)	0.1mH
Load resistor (RL) Load inductor(LL)	20 Ω 10 mH
Filter: Inductor (LF) Resistor (RF)	 1mH 3 Ω
Dc-side capacitance (Cdc)	2100 µF
Reference voltage (Vdc,ref)	400 V
Cascaded multilevel inverter	24- IGBTS/ diodes

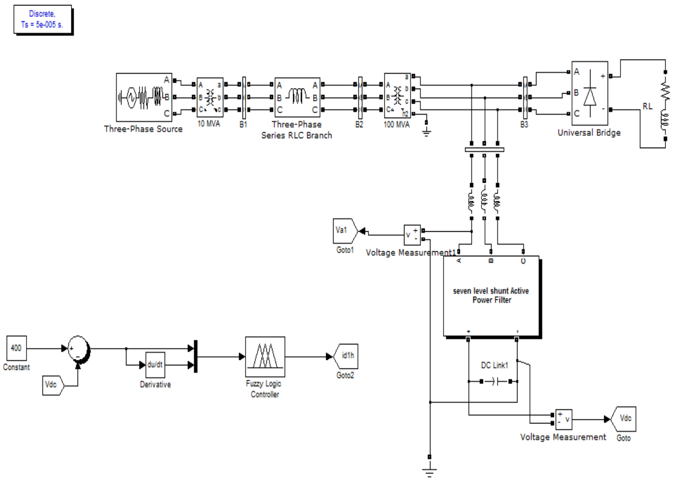

Figure 9. Simulation model of SAPF system with fuzzy controller

The harmonic spectrum of the source current after compensation with fuzzy controller is shown in Fig.12.

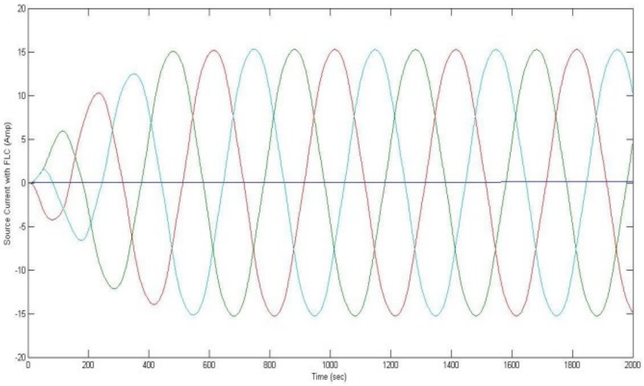

Figure 10. Source current after compensation with FLC

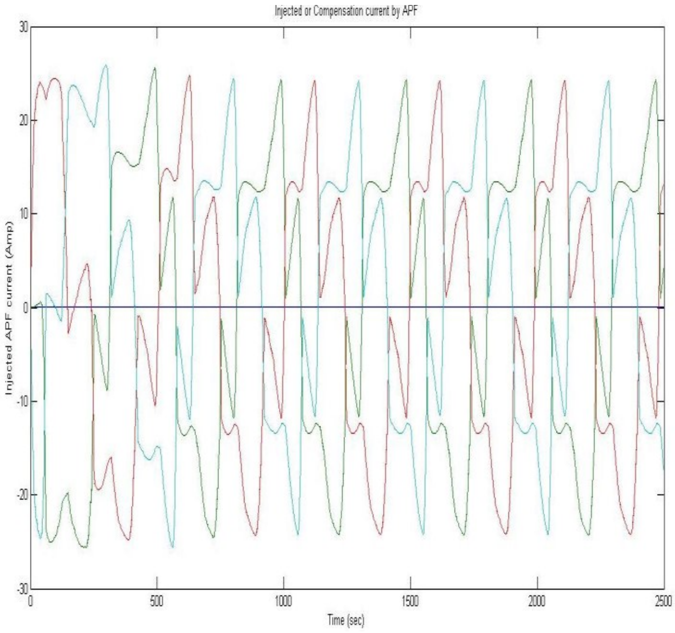

Figure 11. Compensation Current

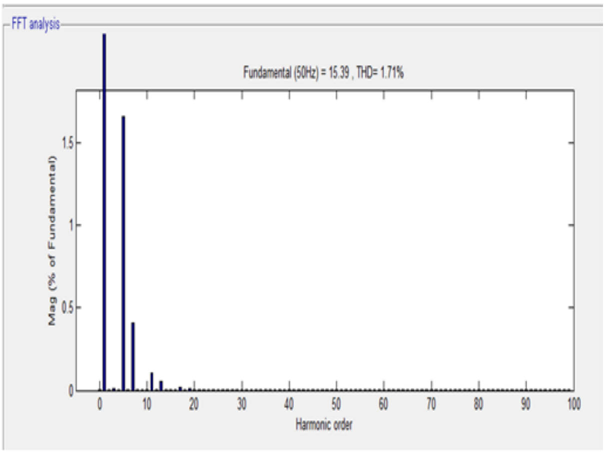

Figure 12. Source current spectrum with fuzzy controller

Table III gives the harmonics performance comparison of uncompensated system and APF with fuzzy controller.

TABLE III HARMONIC PERFORMANCE

System	Source current THD
Uncompensated	28 %
APF With Fuzzy Controller	1.71 %

V. CONCLUSION

In this paper, a five-level cascaded H-bridge multilevel inverter based SAPF incorporating Fuzzy control for dc voltage regulation is presented. The purpose of this filter is to eliminate the harmonics imposed by non-linear loads. To validate the performance of the proposed system extensive simulations are performed on MATLAB/Simulink platform using diode bridge rectifier with RL load. The simulation results justifies the effectiveness of the SAPF system with fuzzy logic controller. The THD of source current is significantly reduced from 28 % to 1.71 % with the use of Fuzzy Logic Controller. The control strategy for reference current extraction based on Synchronous Reference Frame theory provides a better extraction of reference compensation currents from the distorted line current. Thus it is ensured that the proposed SAPF system renders appreciable performance to control shunt active filters based on multilevel inverter topology towards the mitigation of harmonics.

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