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A Novel SAPF for Reduction of Harmonics & Reactive Power with FLC Fed Five-level Cascaded Inverter

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***Abstract*:** The optimization of shunt active power filter parameters based on fuzzy logic control is presented. The current active filter control is based on constant, fuzzy hysteresis band techniques, which are employed to derive the switching signals. The main duty of a shunt APF is to inject into the system a compensating current (active filter current) so as to make the source current sinusoidal and in phase with the source voltage. Pulse Width Modulation (PWM) inverter (with 10 kHz of high switching frequency) has been used for harmonic and reactive power compensation. However, the high initial and running cost have been hindering their practical use in power distribution systems. In addition it is difficult for PWM-inverter based active filters to comply with electromagnetic interference (EMI) requirements. A cascaded multilevel inverter has been proposed for both harmonics and reactive power compensation. This inverter generates almost sinusoidal staircase voltage with only one time switching per line cycle. When cascaded inverter is applied to line conditioning and active power filtering of a distribution system, it is expected that the initial and running costs and the EMI will be dramatically reduced below that of the traditional PWM inverter. This paper presents a compensating system for the harmonic currents, the reactive power and source neutral conductor current in three-phase four-wire distribution system by using a five-level cascaded H-bridge voltage source inverter (CHB-VSI) based shunt active power filter (SAPF). The proposed concept is verified by using Matlab/Simulink software and the corresponding results are presented.

KEYWORDS*:* CHB-VSI; harmonic currents; reactive power Compensation; source neutral conductor current; THD

I. INTRODUCTION

In a modern power system, increasing of loads and nonlinear equipment's have been demanding the compensation of the disturbances caused for them. These non-linear loads may cause poor power factor and high degree of harmonics. Active power filter (APF) can solve problems of harmonic and reactive power simultaneously. APF's consisting of voltage source inverters and a dc capacitor have been researched and developed for improving the power factor and stability of transmission systems. APF have the ability to adjust the amplitude of the synthesized ac voltage of the inverters by means of pulse width modulation or by control of the dc-link voltage, thus drawing either leading or lagging reactive power from the supply. APF's are an up-to-date solution to power quality problems. Shunt APF's allowed the compensation of current harmonics and unbalance, together with power factor correction, and can be a much better solution than conventional approach (capacitors and passive filters). The simplest method of eliminating line current harmonics and improving the system power factor is to use passive LC filters. However, bulk passive components, series and parallel resonance and a fixed compensation characteristic are the main drawbacks of passive LC filters.

Harmonic compensations have become increasingly important in power systems due to the widespread use of adjustable-speed drives, arc furnace, switched-mode power Supply, uninterruptible power supply, etc. Harmonics not only Increase the losses but also produce unwanted disturbance to the communication network, more voltage and/or

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current Stress, etc. Different mitigation solutions, e.g., passive filter, Active power line conditioner, and also hybrid filter, have been Proposed and used. Recent technological advancement of switching devices and availability of cheaper controlling devices, E.g., DSP-field-programmable-gate-array-based system, Make active power line conditioner a natural choice to compensate for harmonics. Shunt-type active power filter (APF) is used to eliminate the current harmonics. The dynamic performance of an APF is mainly dependent on how quickly and how accurately the harmonic components are extracted from the load current. Many harmonic extraction Techniques are available, and their responses have been explored. In this paper a new concept is proposed that is FBD algorithm in three-phase four-wire shunt active power filter to compensate the harmonics.

Multi-level inverters (MLI) as an alternative without a coupling transformer are introduced to generate AC waveform from small voltage steps by utilizing a bank of series capacitors or separate DC sources [7]-[10]. The switching losses and related electromagnetic interference (EMI) are negligible as the switching frequency of MLI is line frequency. Three major types of MLI are realized, namely, diode-clamped, flying-capacitor clamped and cascaded H-bridge voltage source inverter (CHB-VSI) for generating smooth sinusoidal voltage. The cascaded MLI is structured by a number of H-bridge units with a separate DC source for each H-bridge [11]-[12]. The major merits of the CHB-VSI over the other two types are introduced in [13]-[15]. This paper proposes a compensating system based on five-level CHB-VSI. As the five-level CHB-VSI based SAPF with in-phase disposition (IPD) modulation technique which is considered as an effective compensator in a four-wire distribution network, and there it is essential to establish the compensating performance of SAPF. This paper presents the comparative analysis of PI & fuzzy controlled APF to improve PQ features by using Matlab/Simulink platform and results are conferred.

II. ABOUT SHUNT ACTIVE POWER FILTER

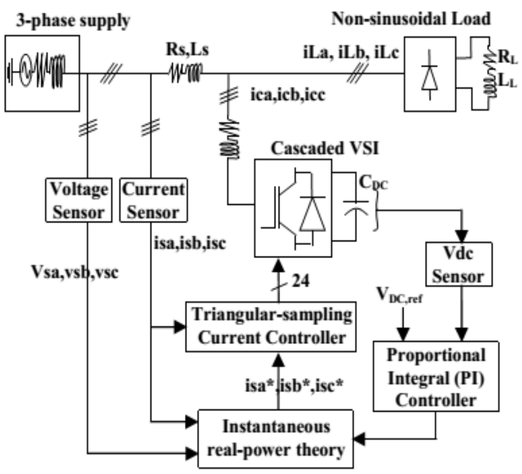

Fig 1 Shunt Active Power Line Conditioners System

Instantaneous real-power theory based cascaded active filter for power line conditioning system is connected in the distribution network at the PCC through filter inductances and operates in a closed loop. The shunt active filter 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 Fig 1. The three-phase supply source connected with non-linear load and these nonlinear loads currents contains fundamental and harmonic components.

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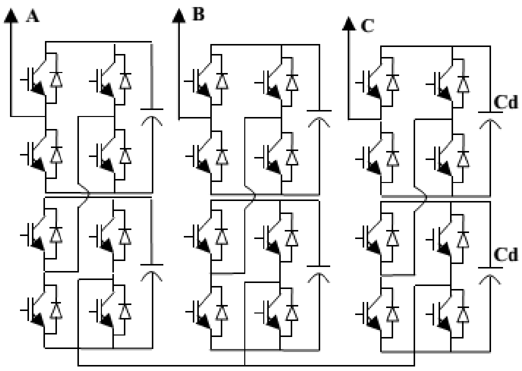

Fig 2 Design of cascaded multilevel active power filter

If the active power filter provides the total reactive and harmonic power, 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 cascaded multilevel active power inverter is constructed by the conventional of H-bridges. The three-phase active filter comprises of 24-power transistors with diodes and each phase consists of two-H-bridges in cascaded method for 5-level output voltage, shown in Fig 2. Each H-bridge is connected a separate dc-bus capacitor and it serves as an energy storage elements to supply a real-power difference between load and source during the transient period. The capacitor voltage is maintained constant using PI-controller. The 24-power transistors switching operations are performed using triangular-sampling current controller and harmonics is achieved by injecting equal but opposite current harmonic components at Point of Common Coupling (PCC).

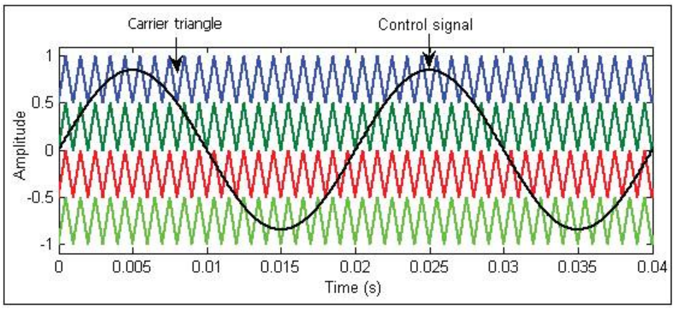

Fig.3 IPD modulation for five-level CHB-VSI

Fig.3 shows the IPD modulation technique uses carriers of same frequency, amplitude and phases, but just differs in DC offset to occupy contiguous bands for five-level VSI. The carriers are in phase across all the bands. In this technique, four triangular carriers are selected for five-level VSI based on the formula M-1 where M is the number of levels, i.e 5-1 = 4 [15].By comparing these 4 triangular carrier signals with the sinusoidal modulation signal, the PWM gating signals for the IGBTs of five-level CHB-VSI will be generated. The simulated output phase voltage and line-to-line voltage of the five-level CHB-VSI and the corresponding harmonic spectrum and total harmonic distribution (THD) respectively.

III. PROPOSED CONTROLLER

The proposed controller shown in Fig. 4 needs less effort and minimum equipment to estimate the reference currents. The controller is developed by sensing the load currents and by using a-b-c to d-q-0transformation (Park transformation).

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$$\begin{bmatrix} i_o \\ i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\omega t) & \sin(\omega t) \\ 0 & -\sin(\omega t) & \cos(\omega t) \end{bmatrix}$$
$$\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

The three-phase instantaneous load currents of the a-b-c coordinates are transformed into synchronous direct axis (d), quadrature axis (q) and zero-sequence reference coordinates (phase quantities to synchronous reference frame) by using Park transformation matrix as in equation (1).

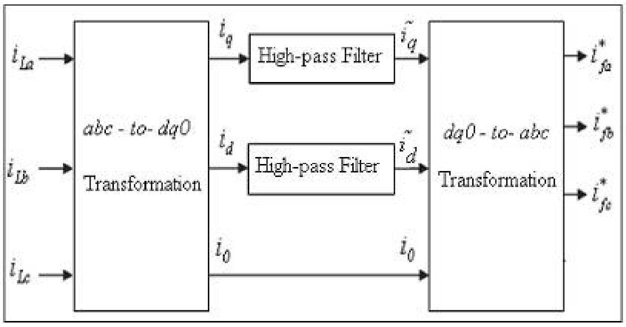

Fig.4 Proposed controller based on the d-q-0 theory

The SAPF controller estimates the reference currents and generates the control signals for the IGBTs of VSI. The estimated reference currents are referred to as and the actual currents injected by the SAPF are referred to as i_{sh} which is illustrated in Fig.5. The measured i_{sh} is compared with and the resulting error is subjected to the IPD modulation technique to generate the gating signals for the IGBT switches. Using inverse Park transformation in equation (1), the phase currents can be obtained as in equation (2).

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\omega t) & -\sin(\omega t) \\ 0 & \sin(\omega t) & \cos(\omega t) \end{bmatrix}$$
$$\begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} \quad (2)$$

The five-level SAPF with the proposed controller aims to inject the compensation currents at the point of common coupling (PCC) in order to suppress the harmonic currents, to minimize the neutral conductor current and to improve the power factor. Fig. 3.2 represents the main power circuit; its consists of a three main parts, viz., generation side, load side and SAPF, also the schematic of SAPF connected at the PCC of the three-phase four-wire distribution network is shown in Fig.5.

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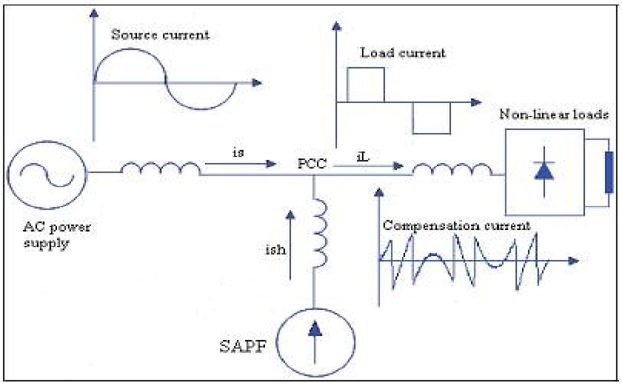

Fig.5 Main power circuit (SAPF in a four-wire distribution network)

IV. FUZZY LOGIC CONTROLLER

L. A. Zadeh presented the first paper on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to APF system. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of APF and performance of proposed controllers. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of APF.

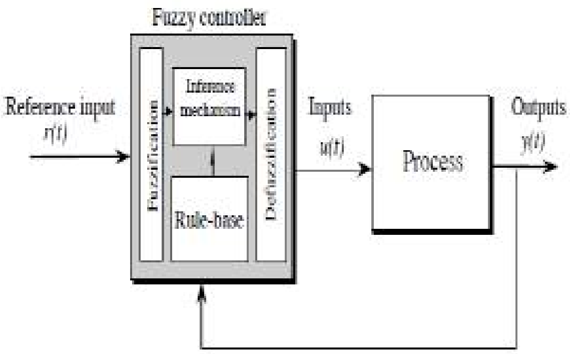

Fig.6. General Structure of the fuzzy logic controller on closed-loop system

The basic scheme of a fuzzy logic controller is shown in Fig 7 and consists of four principal components such as: a fuzzification interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10]. The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical model [10]. Simulation is performed in buck converter to verify the proposed fuzzy logic controllers.

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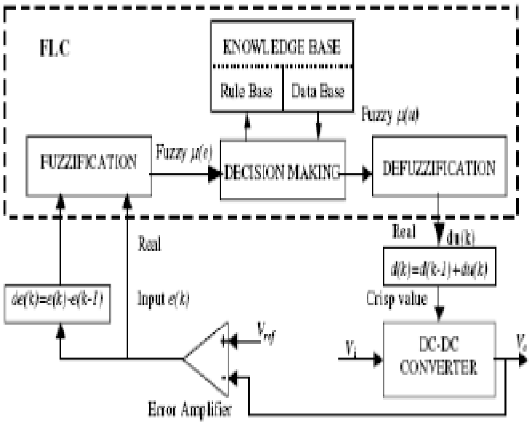

Fig.7. Block diagram of the Fuzzy Logic Controller (FLC) for dc-dc converters

A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database. Firstly, input voltage *Vdc* and the input reference voltage *Vdc-ref* have been placed of the angular velocity to be the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control Current *I*max.

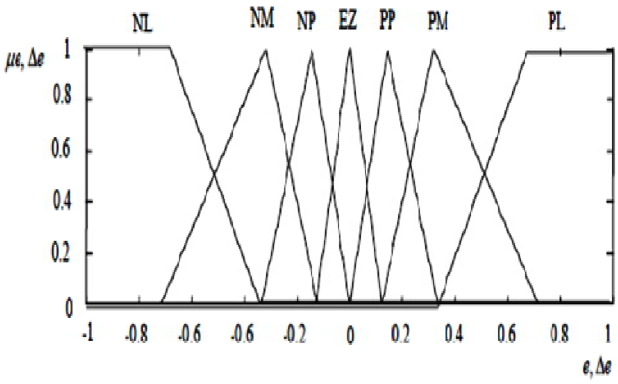

Fig.8 Membership functions for Input, Change in input, Output.

To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) as shown in Fig.8.

Fuzzy Logic Rules:

The objective of this dissertation is to control the output voltage of the boost converter. The error and change of error of the output voltage will be the inputs of fuzzy logic controller. These 2 inputs are divided into five groups; NB: Negative Big, NS: Negative Small, ZO: Zero Area, PS: Positive small and PB: Positive Big and its parameter. These fuzzy control rules for error and change of error can be referred in the table that is shown in Table I as per below:

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Table I
Table rules for error and change of error

Δe \ e	NL	NM	NS	EZ	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	EZ
NM	NL	NL	NL	NM	NS	EZ	PS
NS	NL	NL	NM	NS	EZ	PS	PM
EZ	NL	NM	NS	EZ	PS	PM	PL
PS	NM	NS	EZ	PS	PM	PL	PL
PM	NS	EZ	PS	PM	PL	PL	PL
PL	NL	NM	NS	EZ	PS	PM	PL

V. MATLAB/SIMULINK MODELING & RESULTS

Here simulation is carried out in several cases are used to represent the overall operation of active compensation schemes working under both PI & Fuzzy Controllers.

Case 1: Design of Proposed Five APF Operated under Classical PI Controller

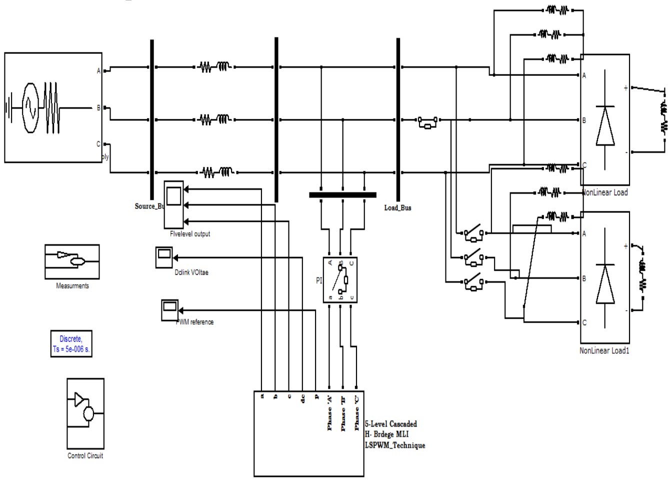

Fig.9 Matlab/Simulink Mode of Proposed Five APF Operated under Classical PI Controller

Fig.9 shows the Matlab/Simulink Mode of Proposed Five APF Operated under Classical PI Controller using Matlab/Simulink package.

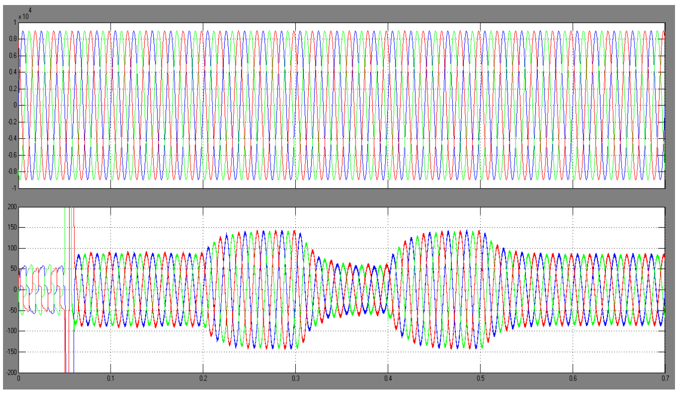

Fig.10 Source Voltage & Current

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Fig.10 shows the Source Voltage & Current of Proposed Five APF Operated under Classical PI Controller.

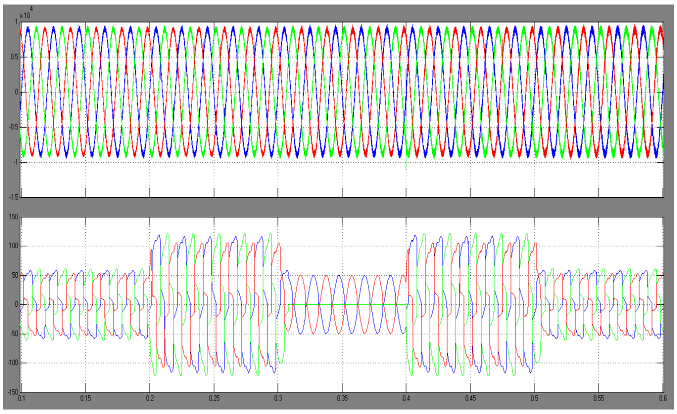

Fig.11 Load Voltage & Current

Fig.11 shows the Load Voltage & Current of Proposed Five APF Operated under Classical PI Controller.

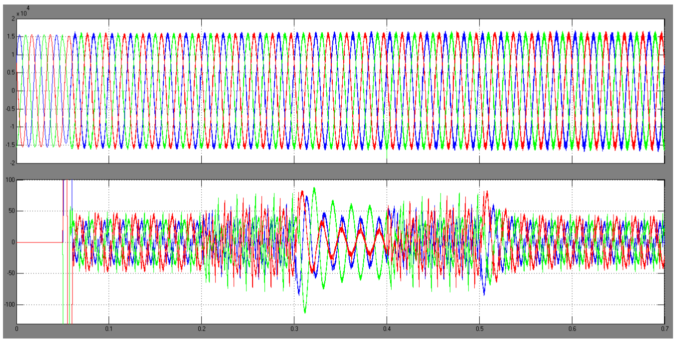

Fig.12 Compensator Voltage & Current

Fig.12 shows the Compensator Voltage & Current of Proposed Five APF Operated under Classical PI Controller.

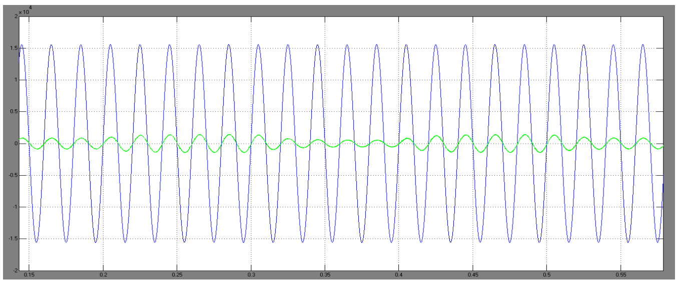

Fig.13 Source Side Voltage & Current in In-Phase Condition

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Fig.13 shows the Source Side Voltage & Current in In-Phase Condition of Proposed Five APF Operated under Classical PI Controller.

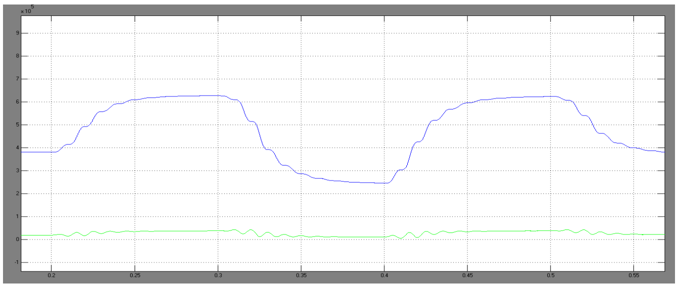

Fig.14 Source Side Active & Reactive Power

Fig.14 shows the Source Side Source Side Active & Reactive Power of Proposed Five APF Operated under Classical PI Controller.

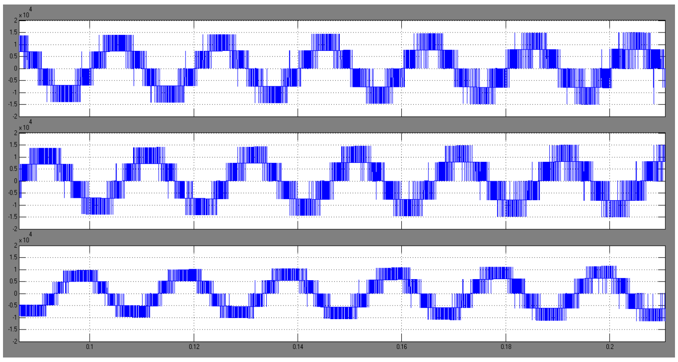

Fig.15 Five Level Output Voltage

Fig.15 shows the Five Level Output Voltage of Proposed Five APF Operated under Classical PI Controller.

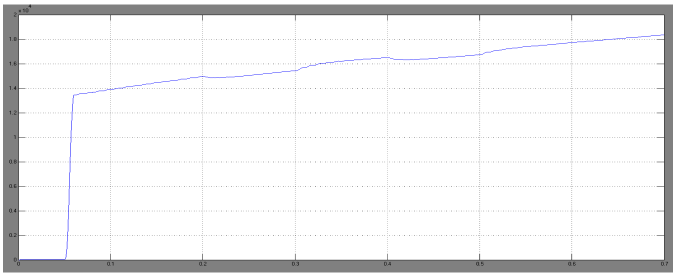

Fig.16 DC Link Voltage

Fig.16 DC Link Voltage of Proposed Five APF Operated under Classical PI Controller.

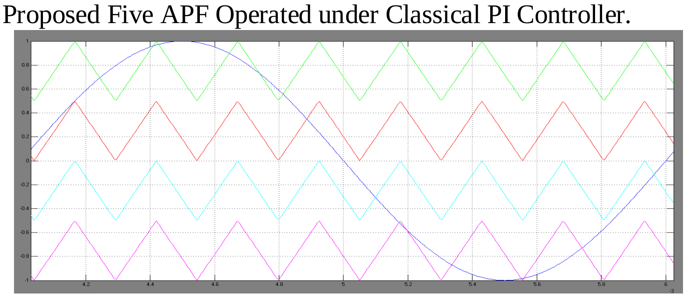

Fig. 17 Switching States- IPD Modulation Scheme

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Fig. 17 Switching States- IPD Modulation Scheme of Proposed Five APF Operated under Classical PI Controller.

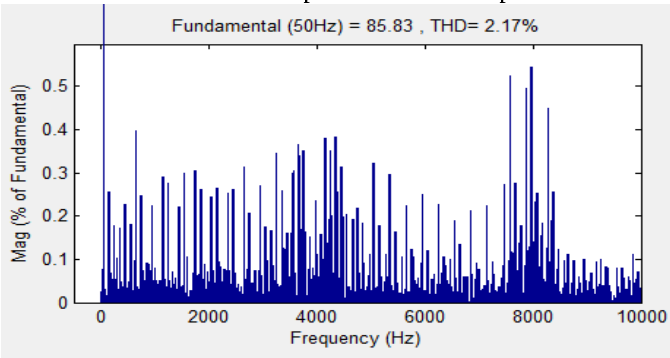

Fig.18 FFT Analysis of Source Current

Fig.18 shows the FFT Analysis of Source Current of Proposed Five APF Operated under Classical PI Controller, attains 2.17%.

Case 2: Design of Proposed Five APF Operated under Classical fuzzy Controller.

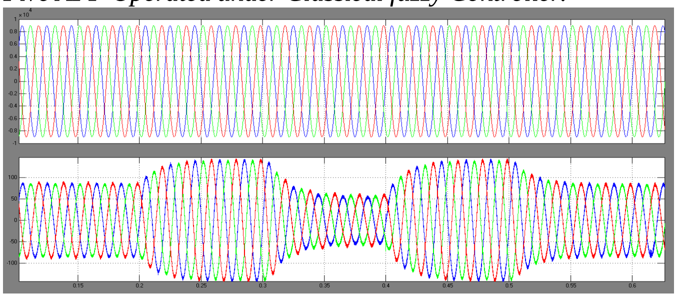

Fig.19 Source Voltage & Current

Fig.19 shows the Source Voltage & Current of Proposed Five APF Operated under Classical Fuzzy Controller.

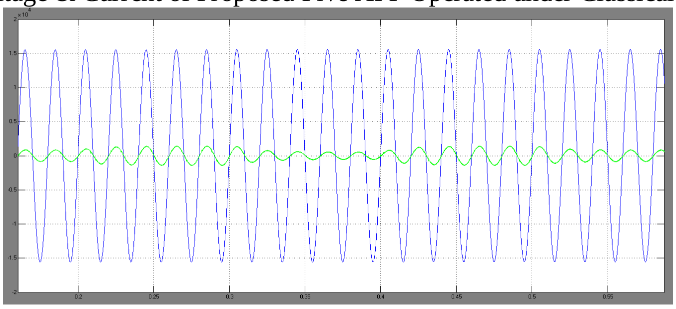

Fig.20 Source Side Power Factor

Fig.20 Source Side Power Factor of Proposed Five APF Operated under Classical Fuzzy Controller.

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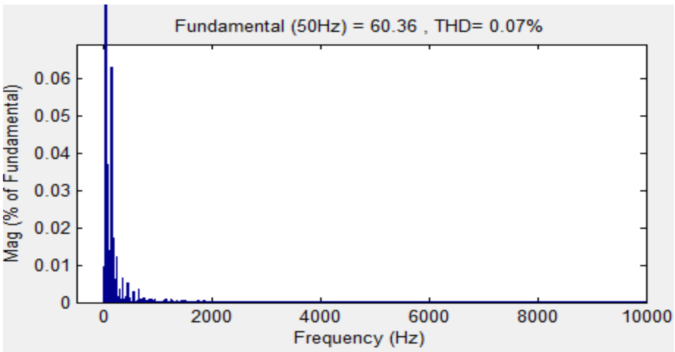

Fig.21 FFT Analysis of Source Current

Fig.21 shows the FFT Analysis of Source Current of Proposed Five APF Operated under Classical fuzzy Controller, attains 0.07%.

VI. CONCLUSION

In this paper Matlab/Simulink model is developed for the proposed five-level CHB-VSI based SAPF by using proposed d-q-0 theory based controller and IPD modulation technique. The performance of five-level CHB-VSI based SAPF with proposed controller is analyzed. It is established from the extensive simulation results that the SAPF is effective to minimize the source harmonic currents and reduce the THD within the prescribed limits of IEEE-519 standards i.e. less than 5 %. The source end power factor is improved closed to unity and the neutral conductor current is also well minimized by the compensating performance of SAPF. The proposed control strategy and modulation technique ensured efficient operation of five-level CHB-VSI based SAPF for power quality improvement of three-phase four-wire distribution systems. Here compare both the performances of PI & Fuzzy controllers, in that fuzzy have better robust performance, THD also well within IEEE standards.

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