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Active Power Conditioner using Fryze-Buchholz-Dpenbrock (FBD) Algorithm

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Abstract- *This paper presents a fuzzy logic controlled shunt active power filter used to compensate for harmonic distortion in three-phase four-wire systems. A shunt APF based on FFT for reference compensating current calculation and fuzzy logic current controller has been studied to improve the system power quality by compensating the harmonic line currents and also the neutral current. The APF provides compensation currents in such a way that the utility supplies only the balanced fundamental current at unity power factor, even if the load draws reactive and harmonic currents. The determination of current references for APF with 4-leg inverter is based on linear adaptive notch filter and instantaneous symmetrical components. The detection algorithm based- on FBD theory for command current in three-phase and four- wire system, can extract the zero-sequence current and harmonic current from the load current. It is applied by considering a balanced and resistive load as ideal load, so that the voltage waveform injected by the active filter is able to compensate the reactive power, to eliminate harmonics of the load current and to balance asymmetrical loads.*

Keywords-Fuzzy, Three-phase and four-wire; active power filter (APF); Fryze-Buchholz-Dpenbrock (FBD); Hysteresis control;

I.INTRODUCTION

In recent years, power quality distortion has become a serious problem in electrical power systems due to the increase of nonlinear loads drawing non-sinusoidal currents. Active filters have been widely used for harmonic mitigation as well as reactive power compensation, load balancing, voltage regulation, and voltage flicker compensation. In three-phase four-wire systems with nonlinear loads a high level of harmonic currents in both the three line conductors and more significantly in the neutral wire has been enrolled. Unbalanced loads also results in further declination of the supply quality.

Eminent issues always arises in three-phase four-wire systems. It is well-known the that zero line may be overheated or causes a fire as a result of excessive harmonic current going through the zero line three times or times that of three. Thus a perfect compensator is necessary to avoid the negative consequences of harmonics. Though several control techniques and strategies have been developed they still have contradictions with the performance of filters. These issues became the primary motivation for this paper. This paper focuses mainly on two controllers i.e., fuzzy. In addition, a filter was developed with the instantaneous active and reactive current method.

Traditionally, a passive LC power filter is used to eliminate current harmonics when it is connected in parallel with the load [3], [4]. This compensation equipment has some drawbacks [5] mainly related to the appearance of series or parallel resonances because of which the passive filter cannot provide a complete solution. The APF can be connected either in parallel or in series with the load. The first one is especially appropriate for the mitigation of harmonics of the loads called harmonic current source. In contrast, the series configuration is suitable for the compensation of loads called harmonic voltage source. The shunt connection APF is the most studied topology [6]–[10]. However, the costs of shunt active filters are relatively high for large-scale system and are difficult to use in high-voltage grids. The increasing use of rectifiers, thyristor power converters, arc furnaces, switching power supplies and other non linear loads is known to cause serious problems in electric power systems.

These problems can be partially solved with the use of passive filters, however, this kind of filtering cannot adapt to variations of the loads, and they also can produce undesired resonances [2]. One solution to avoid these problems is the Shunt Active Power Filter. These devices work as current sources, connected in parallel with the electric grid, and they are capable of providing the harmonics and the reactive power required by the loads [3]. Three-phase four-wire Shunt Active Power Filters are also capable of compensating unbalance and zero sequence currents, minimizing the neutral current [4]. In this way, the mains only supply the fundamental, balanced currents with a unitary power factor, avoiding voltage distortion and reducing power losses in the transmission lines.

PQ problems arise when nonlinear single-phase loads are connected to three-phase, four-wire systems. Even if these loads are perfectly balanced, harmonic currents circulate through the neutral conductor, which will always occur due to the existence of zero sequence components. The amplitudes of these currents may exceed those of the individual phase current, which can cause damage to the neutral conductor and to the transformers where the loads are connected[1-3].

An alternative method to solve or minimize these problems is the use of shunt active power filters (APFs), applied in single-phase and three-phase three-wire and four-wire systems. APFs are used to inject in the line, compensation currents in order to cancel harmonics and/or reactive components of the load currents. For three-phase four-wire systems, depending on the control strategies adopted, the APF can control each phase independently. Thus, it is possible to compensate all the harmonic and reactive current components. In this case, the compensation of the unbalanced load is not taken into account [7]. Active power filter (APF) of three-phase three-wire has been widely applied[4]. While it is only suitable for the balance three phase system but not unbalance three phase system[5]. APF of three-phase four-wire can compensate the zero- sequence component effectively which means that it is very suitable to compensate the three-phase four-wire system[6]. Command current detection algorithm of three-phase four-wire system based on improved Fryze-Buchholz-Dpenbrock (FBD) algorithm is proposed to eliminate the influence of zero- sequence component. A three-leg APF of three-phase four-wire system is studied.

II. MAIN CIRCUIT STRUCTURE OF THREE-LEG THREEPHASE FOUR-WIRE APF

Main circuit structure of three-phase four-wire APF based on the three-leg circuit has two kinds that one is based on the split-phase capacitor and the other one is based on three-leg topology. There are merits and faults of each. 8 IGBTs and 4 current limited reactors are required in the 4-leg main circuit structure. And because of the existence of forth leg among three phases, decoupling of the phase control of system can be realized. But the 4-leg structure is expensive. At the same time, with only 6 IGBTs and 3 reactors, 3-leg structure with split phase capacity is much cheaper. But the voltage of split-phase capacity vibrates largely, and the balance control of direct current (DC) bus voltage is complex. Considering the costs and that the capacity of prototype blows 100KVA, 3-leg structure with split-phase capacity is selected.

Main topology of three-phase four-wire APF with 3 legs is shown in Fig. C1 and C2 are split-phase capacities; they have the same voltage value, withstand voltage and capacity. Zero line of the system is connected to the neutral point of DC bus to provide the circulation path of compensate current of zero line. And the main circuit of APF is connected to the grid and load through series current limited reactors.

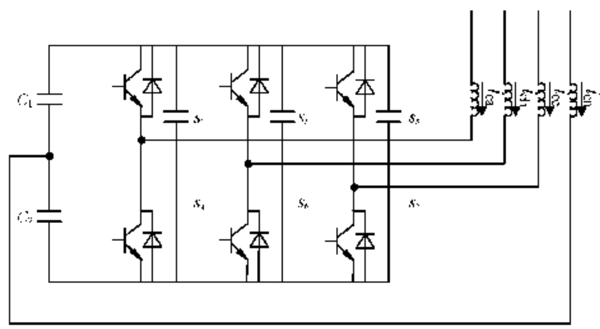

Fig.1. Main circuit structure of APF

III. WORKING PRINCIPLES OF THREE-PHASE FOUR-WIRE APF WITH THREE LEGS

Block diagram of APF is shown in the Fig. 2. SVG with three legs consists of command current detection module, DC bus voltage control module and average voltage of split-phase capacities in DC bus control module. The workflow of three phase four-wire APF with three legs is as followed. After put into work, three-phase load current and three-phase compensate current of APF are detected and then, through a sampling circuit, transported to digital signal processor (DSP) in which command signal of compensate current is obtained based on the improved FBD algorithm. Then drive pulse is produced by the hysteretic control of command signal. After the power amplification, the drive pulse will be put on the gate of IGBT to complete the compensate work. In this process, DSP has real-time communication with host

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computer, receiving instruction of parameter modification from host computer and sending parameter needed by host computer. In addition, voltages of DC bus and split-phase capacities are required to control the voltage of DC bus and the result will play a role in the calculation of command current [5].

A. Improved FBD Algorithm

FBD algorithm was proposed by German scholar Fryze in 1930s and then improved by others like F. Buchholz and becomes FBD algorithm in contemporary finally. It has good real-time property and simple calculation and is not only suitable for three-phase system but also for the multi-phase. While, for the three-phase four-wire system, the study of the algorithm is limited to the theoretical research I long time. Compared with traditional ip-iq algorithm, the FBD harmonic detection has a different expression in the energy flow and is simpler in calculation in the extraction process of command current. The fundamental thought of calculation of command current is as followed. Initially, loads in each phase of APF should be transformed to the equivalent conductance on which all energy of system is considered to be consumed without other loss. And then, load current can be decomposed into parts including harmonics component and reactive power component. Based on the positive sequence component of unbalanced and non-sinusoidal voltage, reference voltage signal which is in phase with positive sequence component of three phase fundamental wave can be extracted and restored by phase locked loop (PLL). At last, after the calculation using the reference voltage and three phase load current with zero sequence separation, active power component of three phase fundamental wave can be achieved.

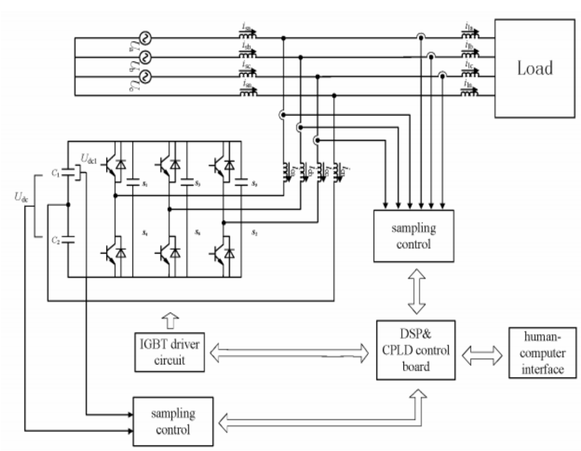

Fig 2. Block diagram of APF

However, as for the three-phase four-wire system with unbalanced three phase, the traditional FBD algorithm cannot be applied directly with the lack of zero-sequence detection. So, before the calculation of command current, zero-sequence component should be separated from the load current.

$$\begin{bmatrix} u_a(t) \\ u_b(t) \\ u_c(t) \end{bmatrix} = \begin{bmatrix} \sin \omega t \\ \sin(\omega t - \frac{2}{3}\pi) \\ \sin(\omega t + \frac{2}{3}\pi) \end{bmatrix} \quad (1)$$

$$\begin{cases} i_a(t) = \sum_{k=1}^{\infty} I_{ak}^{+} \sin(k\omega t + \varphi_k^{+}) + I_{ak}^{+} \sin(k\omega t + \varphi_k^{-})] \\ i_b(t) = \sum_{k=1}^{\infty} I_{bk}^{+} \sin(k\omega t + \varphi_k^{+} - \frac{2}{3}\pi) + I_{bk}^{+} \sin(k\omega t \\ \qquad + \varphi_k^{-} - \frac{2}{3}\pi)] \\ i_c(t) = \sum_{k=1}^{\infty} I_{ck}^{+} \sin(k\omega t + \varphi_k^{+} + \frac{2}{3}\pi) + I_{ck}^{+} \sin(k\omega t \\ \qquad + \varphi_k^{-} + \frac{2}{3}\pi)] \end{cases} \quad (2)$$

$$G_p(t) = \frac{\langle u,i \rangle}{\langle u,u \rangle} = \frac{u_a(t)i_a(t) + u_b(t)i_b(t) + u_c(t)i_c(t)}{u_a(t)^2 + u_b(t)^2 + u_c(t)^2} = \frac{1}{\frac{3}{2} - \cos 2\omega t}[u_a(t)i_a(t) + u_b(t)i_b(t) + u_c(t)i_c(t)] \quad (3)$$

$$G_p(t) = I_{a1}\cos\varphi_{a1} + I_{b1}\cos\varphi_{b1} + I_{c1}\cos\varphi_{c1} \quad (4)$$

$$i_p(t) = G_p(t) \begin{bmatrix} \sin \omega t \\ \sin(\omega t - \frac{2}{3}\pi) \\ \sin(\omega t + \frac{2}{3}\pi) \end{bmatrix} = \begin{bmatrix} i_{a1}(t) \\ i_{b1}(t) \\ i_{c1}(t) \end{bmatrix} \quad (5)$$

B. Average Voltage Control of Split-Phase Capacitors

Circuit structure with split-phase capacitor is proposed. In the unbalanced three phase system, zero-sequence component of three phase flows back to the neutral line through capacitors C1 or C2 which may cause the voltage concussion of split phase capacitors. And if the amplitude of concussion is extensive, the stability of DC bus voltage would be lost and the compensation of SVG would be influenced. So the average voltage control of split-phase capacitors is in need. Voltage changes of split-phase capacitors are shown in the Table 1. As shown in the Table 1, when ick > 0, the voltage of C1 will hike and the voltage of C2 will descend. However, when ick <

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0, the condition is in opposite. And this is the principle of voltage concussion.

Compensation command current detection algorithm of APF system which combines the average voltage control with FBD algorithm is shown in Fig. 3.The DC bus voltage control of three-phase three-wire system is achieved as followed. The real-time sampled values of DC bus voltage is compared with the given value, then, the result will be stacked on the linear conductance branch circuit which stands for the active power in the FBD method after passing through the proportional integral (PI) control.

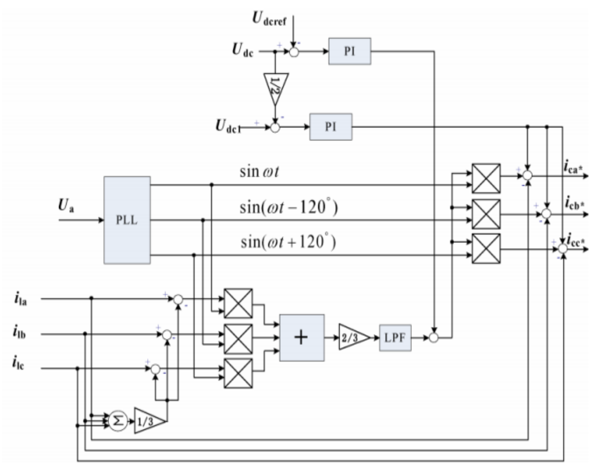

Fig 3. Command current algorithm based on the improved FBD method

And the average voltage control of three phase four-wire system is adding an outer loop control based on the DC bus voltage PI control. The voltage of split-phase control is compared with the half of the DC bus voltage reference. After the calculation of PI control, the result is added on the output of command current and the average voltage control is completed.

IV. ABOUT FUZZY CONTROLLER

Fig. 4 shows the internal structure of the control circuit. The control scheme consists of Fuzzy controller, limiter, and three phase sine wave generator for reference current generation and generation of switching signals. The peak value of reference currents 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 a Fuzzy controller, which contributes to zero steady error in tracking the reference current signal.

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 V_{dc} and the input reference voltage $V_{dc\text{-}ref}$ 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}. 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.5.

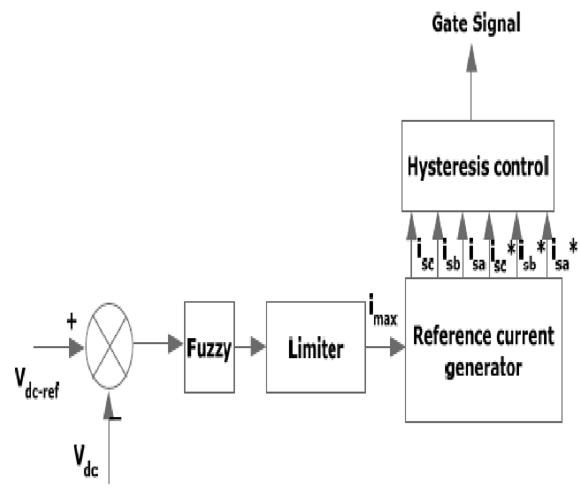

Fig.4. Fuzzy Controller

The fuzzy controller is characterized as follows:
1) Seven fuzzy sets for each input and output;
2) Fuzzification using continuous universe of discourse;
3) Implication using Mamdani's 'min' operator;
4) De-fuzzification using the 'centroid' method.

Fuzzification: the process of converting a numerical variable (real number) convert to a linguistic variable (fuzzy number) is called fuzzification.

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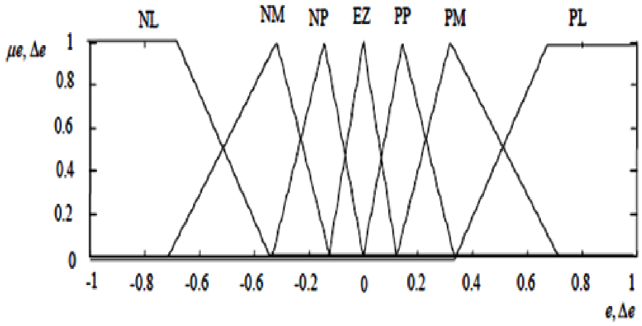

Fig.5. Membership functions for Input, Change in input, Output.

De-fuzzification: the rules of FLC generate required output in a linguistic variable (Fuzzy Number), according to real world requirements, linguistic variables have to be transformed to crisp output (Real number).

Database: the Database stores the definition of the membership Function required by fuzzifier and defuzzifier.

Rule Base: The elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse in-put/output variables; in the steady state, small errors need fine control, which requires fine input/output variables. Based on this the elements of the rule table are obtained as shown in Table 1, with '*Vdc*' and '*Vdc-ref*' as inputs.

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

IV. MATLAB MODELEING AND SIMULATION RESULTS

Here the simulation is carried out in two cases 1.Implementation of proposed converter using conventional PI controller. 2. Implementation of proposed converter using fuzzy logic controller.

Case 1: Implementation of proposed converter using conventional PI controller with PV model.

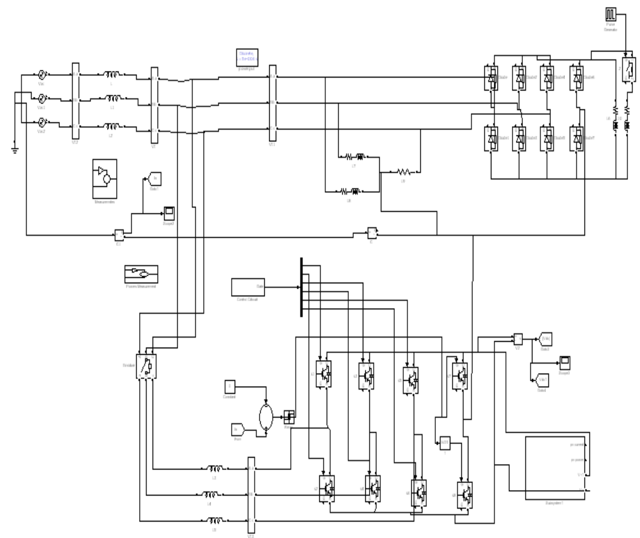

Fig.. 6 Matlab/Simulink Model of Proposed Power Circuit

Fig. 6 shows the complete MATLAB model of proposed power circuit along with control circuit. The power circuit as well as control system are modeled using Power System Block set and Simulink.

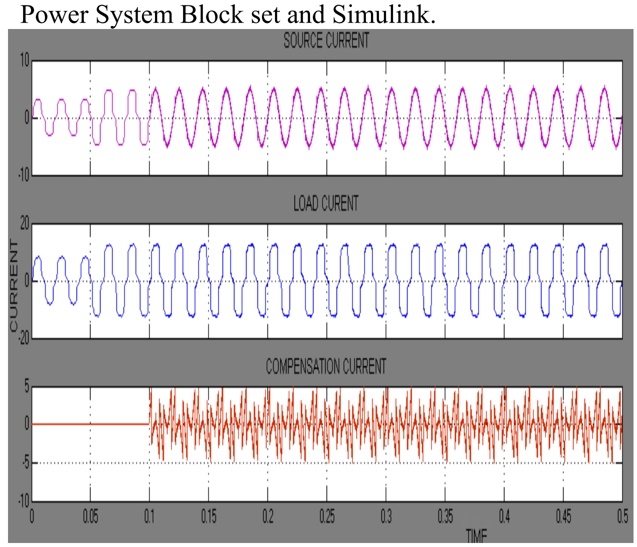

Fig..7. Simulation results for Un Balanced Non Linear Load using PI controller (a) Source current. (b) Load current. (c) Inverter injected current.

Fig.7. shows the source current, load current and compensator current respectively. Here compensator is turned on at 0.1 seconds.

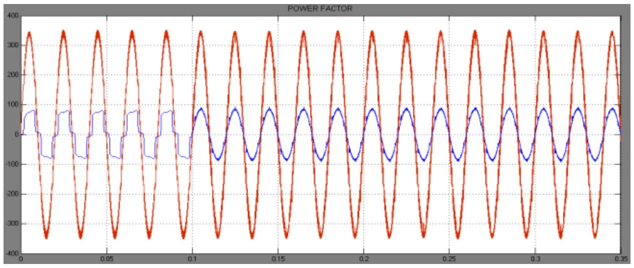

Fig..8. Simulation results power factor for Un balanced Non linear Load

Fig.8 shows the power factor it is clear from the Fig. after compensation power factor is unity.

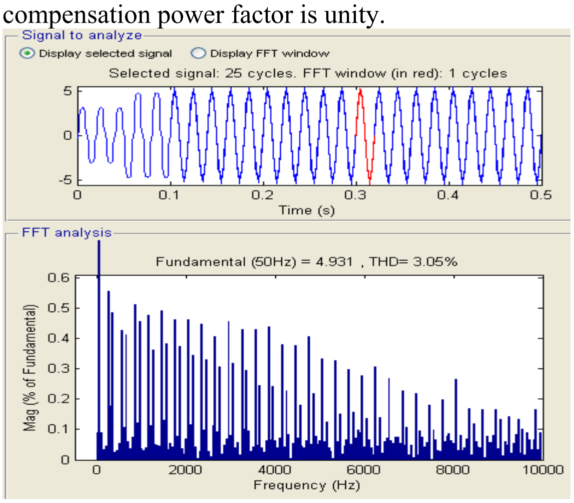

Fig.9. THD for inverter using PI controller

Fig.9. shows the THD analysis of the source current using the PI controller, we get 3.05%.

Case 2: Implementation of proposed converter using fuzzy logic controller:

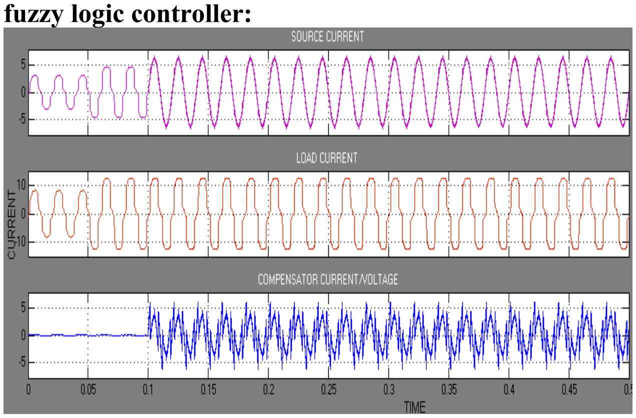

Fig:10 Simulation results for Un Balanced Non Linear Load using fuzzy controller (a) Source current. (b) Load current. (c) Inverter injected current

Fig.10. shows the simulation results of proposed converter using fuzzy logic controller, Source current, load current, compensating current respectively.

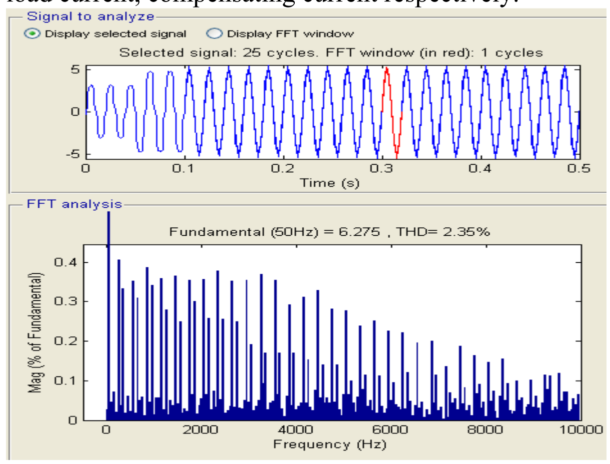

Fig.11 THD for inverter using fuzzy controller

Fig.11 shows the THD analysis of the source current using the fuzzy controller, we get 2.35%.

V.CONCLUSION

Both PI controllers based and fuzzy logic controller VSI based shunt active power filter are implemented for harmonic and reactive power compensation of the non-linear load. A circuit has been developed to simulate the fuzzy logic based and PI controller based shunt active power filter in MATLAB. A SVG for the unbalanced three-phase phenomenon in the three-phase four-wire system is designed. The flow path of neutral line current is provided by the split-phase capacitors in the DC bus. Based on the improved FBD algorithm, command current detection algorithm of APF is designed. Dynamic hysteresis band control is applied to achieve the simultaneous compensation of harmonics and reactive power. In this way, power factor at grid side can up to 0.998. The correctness of control strategy and favorable compensation performance of APF for the harmonics and reactive power is testified by the result. The performance of both the controllers has been studied and compared. A model has been developed in MATLAB SIMULINK and simulated to verify the results. The THD of the source current is below 5%, the harmonics limit imposed by IEEE standard.

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