FUZZY Logic Based Space Vector PWM Controlled Hybrid Active Power Filter for Power Conditioning

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Abstract:- This paper investigates the comparative analysis of a Hybrid Active Power Filter with PI based SVPWM controller and fuzzy based space vector PWM controller for mitigating the harmonics, improving the power factor and increasing the distribution power of the three phase distribution system. This paper concluded that the power conditioning by fuzzy based SVPWM hybrid active power filter is superior than PI controller based SVPWM technique. In the proposed control filters three control circuits are used such as PI control unit, fuzzy unit and SVPWM control unit. Fuzzy arithmetic's are used for adjusting proportional–integral coefficients timely. The desired output voltage is generated based on generated reference voltage by fuzzy based SVPWM. A MATLAB code is developed to generate the SVPWM switching pulses fed to the two-level inverter topology. Simulations are carried out using MATLAB. It is found that the %THD has been improved from 2.67 to 1.57and power factor is improved to 0.9718. The simulation results shows that the effectiveness and feasibility of the proposed filter.

Key words:- Hybrid Active Power Filter, Fuzzy Logic Controller, IGBT Inverter, Space Vector PWM, Total Harmonic Distortion (THD), Distribution system.

1 Introduction

Power quality is the main problem that the industry is facing today. The quality of power has been deteriorating with the presence of various current and voltage harmonics, low power factor, voltage sags and swells, flicker and many other disturbances. Among the various disturbances, Harmonic distortion [1] is one of the most serious power quality problems. Particularly, in the distribution systems, harmonics are the major concerned problem. The growing use of electronic equipments is one of the major causes to impute the harmonics, which led to distortion of voltage and current waveforms and increased reactive power demand in ac mains as they pass through the system impedance.

However, in the present situation various power quality improvement solutions are available; Isolate harmonic loads on separate circuits (with or without harmonic filters), Harmonic mitigating transformers, Phase shifting (zig-zag) transformers, Filter capacitor banks, Line Reactors, K-Rated / Drive Isolation Transformers, Harmonic Mitigating / Phase Shifting Transformers, Passive parallel / series tuned Filters and Active Filters[2-4].

Passive filtering is the simplest conventional solution to reduce the harmonics. But they have many demerits such as; a) the number of passive filters installed would depend on the number of harmonic component to be compensated, this demands for the information of harmonic content to be know in advance. b) These cannot function under the saturated conditions, c) At some frequencies, these filters may lead to resonance. All the above demerits of the filters are overcome by the use of active filters. But, for high-power applications, the Active filters are not cost effective due to their large rating and high switching-frequency requirement of the pulse width modulation inverter. For harmonic current tracking controls, there are two schemes .One is the linear current control and the other is nonlinear current control. Hysteresis nonlinear control method is simple but leads to a widely varying switching frequency [5]. This limitation has been improved with variable hysteresis band switching strategies but it requires a complex controller to achieve satisfactory performance. Predictive current control offers the best potential for precise current control, but the implementation of a practical system can be difficult and complex.

Recently, fuzzy logic controllers (FLC) [6-8] have received a great deal of attention for their application in active power filters (APFs). The advantages of FLC over conventional controllers are that they do not require an accurate mathematical model, can work with imprecise inputs, can handle non-linearity and are more robust than the conventional controllers. The Mamdani type of FLC is used for the control of an APF and it gives better results, but it has the drawback of a larger number of fuzzy rules.

In this paper, Fuzzy based SVPWM controller was proposed. The proposed controller filter shows shorter response time and higher control precision. The simulation results also show that the new control method is not only easy to be calculated and implemented, but also very effective in reducing harmonics.

2 Principal of operation

In each switching cycle the controller samples are the supply current i_a, i_b & i_c are calculated as

$$-i_a=i_b+i_c \quad (1)$$

As the summation of three supply currents is zero. These three phase supply currents are measured & transformed into direct & quadrature axis components of two dimensional planes. The fundamental component of supply currents are transformed into d-q axis & supply current amplitude I_s is generated. That I_s is controlled by the fuzzy controller with V_{dc} & V_{ref} (Reference value of DC bus voltage). The output of fuzzy controller is equivalent to reference voltage vector. By using Fourier magnitude block, voltage magnitude & angle is calculated. From the obtained signal, these values are fed to developed code & compare to the relative sequence. The generated switching actions are applied to & balancing of the filter takes place.

3 Configuration of hybrid active power filter

Fig.1 shows the proposed hybrid active power filter with non linear load consist of both active & Passive Filter. The Passive filter connected in shunt with the distribution system and is tuned to present low impedance at a particular harmonic current. The shunt active passive filter takes a three phase voltage source inverter as the main circuit & uses capacitor (C) as the Voltage storage element on the DC side to maintain the DC bus voltage V_{DC} constant. The hybrid active power filter is implemented with fuzzy based SVPWM current controlled voltage source inverter (VSI) and is connected at the point of common coupling for compensating the current harmonics and reactive power. This system is investigated and the performances of parameters are verified under different non-linear load conditions [1].

It can be assumed that the supply voltage and current is ideal and sinusoidal and the three-phase balanced parameters are shown as below:

$$V_{sa} = V_s Sin(wt) \quad (2)$$

$$V_{sb} = V_s Sin(wt - \tfrac{2\pi}{3}) \quad (3)$$

$$V_{sc} = V_s Sin(wt + \tfrac{2\pi}{3}) \quad (4)$$

Where V_s represents the supply voltage. If equations (2), (3) and (4) are the three phase voltages. [Vsa Vsb Vsc] in a-b-c can be expressed as two-phase representation in d-q reference frame by Clark's transformation and it is given by equation (5).

$$(Is) = \frac{Id}{Iq} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{pmatrix} Isa \\ Isb \\ Isc \end{pmatrix} \quad (5)$$

Above equation can be reduced as

$$I_s = \frac{2}{3}[I_{sa}a^0 + I_{sb}a^1 + I_{sc}a^2] = I_d + JI_q = I_s\angle\theta^s \quad (6)$$

Where $a=e^{j2/3\pi}$, θ^s is angle of supply current.

For nonlinear load

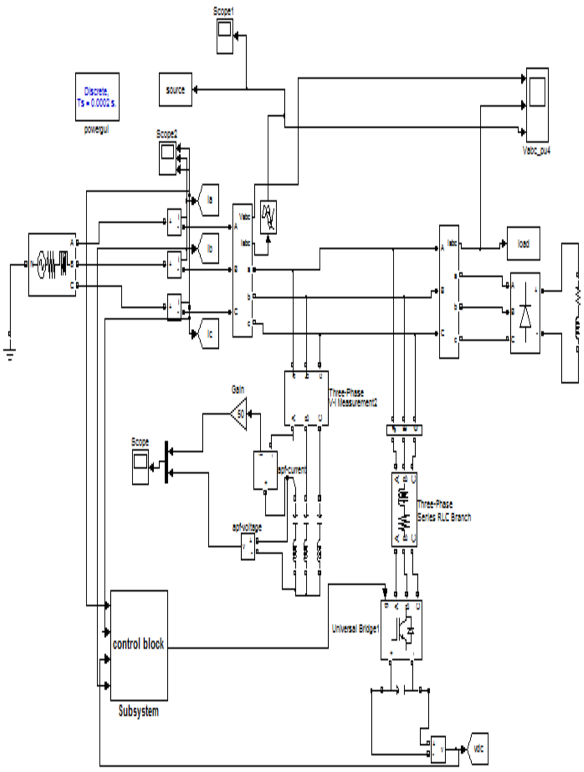

Fig.1 Proposed hybrid active power filter for nonlinear load

4 Compensation Principle

Fig.2 and Fig.3 shows the equivalent circuit and equivalent impedance circuit model of hybrid active power filter system described in Fig.2.

In the Fig.2, if $v_{fa,1}$ and $v_{fa,h}$ denote the output fundamental and harmonic voltages of the inverter, respectively. These voltage sources are connected to a supply source (v_s) in parallel via a link inductor L_{af} and capacitor C_{af} of the impedance is Zaf. The supply current i_s is forced to be free of harmonics by appropriate voltages from the APF and the harmonic current emitted from the load is then automatically compensated.

It is known from Fig.4.1, that only fundamental component is taken into account, the voltages of the ac supply and the APF exist the following relationship in the steady state

$$\bar{V}_s = L_{af} \cdot \frac{d\bar{I}_{inv}}{dt} + \frac{1}{C_{af}} \int \bar{I}_{inv} dt + \bar{V}_{af} \quad (7)$$

Where $\bar{V}_s$ is the supply voltage, $\bar{I}_{inv}$ is the fundamental current of APF, $\bar{V}_{af}$ is the fundamental voltage of APF, and above variables are expressed in form of space vector. The APF is joined into the network through the inductor L_{pf} and $C_{pf.}$ Of the impedance Zpf . The function of these filter is to reduce higher harmonics nearly switching frequency in the current and to link two ac voltage sources of the inverter and the load network. So the required inductance and capacitance can just adopt a small value. Then the total reactance caused by inductor and capacitor for the frequency of 50Hz, and the fundamental voltages across the link inductors and capacitors are also very small, especially compared with the mains voltages. Thus the effect of the voltage of the link inductor and capacitor is neglected. So the following simplified voltage balanced equation can be obtained from equation (7).

$$\bar{V}_s = \bar{V}_a f \quad (8)$$

The control object of APF is to make the supply current sinusoidal and in phase with the supply voltage. Thus the nonlinear load and the active power filter equals to a pure resistance load R_s, and the supply voltage and the supply current satisfy the following equation:

$$\bar{V}_s = R_s \cdot I_s \quad (9)$$

where

$$\bar{I}_s = \frac{2}{3}\left(i_{sa}a^0 + i_{sb}a^1 + i_{sc}a^2\right) = I_{sd} + jI_{sq} = I_s \angle \theta_i .$$

Then the relationship between I_s and the supply voltage amplitude V_s is

$$V_s = R_s I_s \quad (10)$$

Substituting (9), (10) into (8) results in

$$\bar{V}_{f1} = \frac{V_s}{I_s} \cdot \bar{I}_s \quad (11)$$

Equation (11) describes the relationship between the output_fundamental voltage of APF, the supply voltage and the supply current, which ensure that the APF operate normally. However, for making the APF normally achieving the required effect, the dc bus voltage V_{DC} has to be high enough and stable. In the steady state, the power supplied from the supply must be equal to the real power demanded by the load, and no real power passes through the power converter for a lossless APF system. Hence, the average voltage of dc capacitor can be maintained at a constant value. If a power imbalance, such as the transient caused by load change, occurs, the dc capacitor must supply the power difference between the supply and the load, the average voltage of the dc capacitor is reduced. At this moment, the magnitude of the supply current must be enlarged to increase the real power delivered by the supply. On the contrary, the average voltage of the dc capacitor rises, and the supply current must be decreased. Therefore, the average voltage of the dc capacitor can reflect the real power flow information. In order to maintain the dc bus voltage as constant, the detected dc bus voltage is compared with a setting voltage. The compared results is fed to a fuzzy based controller, and amplitude control of the supply current I_s can be obtained by output of fuzzy based controller.

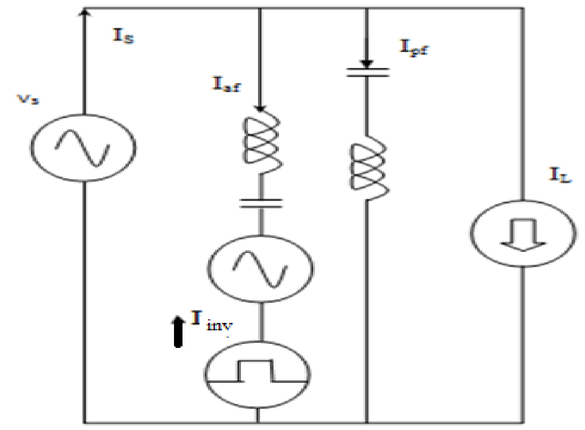

Fig.2 Equivalent circuit of hybrid active power filter

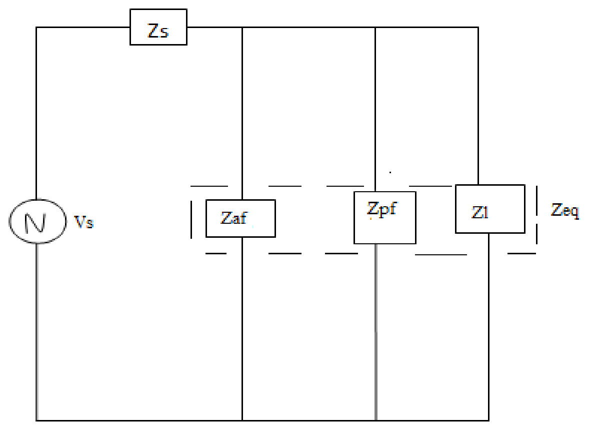

Fig. 3 Equivalent impedance circuit model

$$I_s = \frac{V_s + V_{inv} - I_{af} Z_{af}}{Z_s} \quad (12)$$

$$I_l = \frac{-Vinv}{(Zpf * Zl)} - Iaf \frac{Zaf(Zpf + Zl)}{(zpf + Zl)} \quad (13)$$

Where Is=source current ,Vs = source voltage, Vinv =inverter voltage, Iaf = current passing through active filter , Ipf=current passing through passive filter, Zaf= impedance offered by active filter, Zpf=impedance offered by passive filter, Zl=load impedance .

Total impedance of hybrid active power filter

$$Z_{eq} = \frac{Zl * Zpf((Zaf * Zl) + (Zpf * Zaf))}{(Zl * Zpf) + ((ZafZl) + (ZafZpf))} \quad (14)$$

Total voltage from Fig.3 is calculated by

$$Vs - IsZs = I_L Z_{eq} \quad (15)$$

Zeq = Equivalent impedance offered by active filter, passive filter and load.

5 Control strategies of hybrid active power filter

5.1 Control Block Diagram of Fuzzy Based SVPWM Controller

The Fig.4 shows the block diagram of active filter controller implemented for reducing the harmonics with hybrid active filter system. In each switching cycle, the controller samples the supply currents i_a, i_c and the supply current i_c is calculated with the equation of $-(i_a+i_c)$, as the summation of three supply current is equal to zero.

These three-phase supply currents are measured and transformed into synchronous reference frame (d-q axis). The fundamental component of the supply current is transformed into dc quantities in the (d-q) axis and the supply current amplitude I_s generated by the fuzzy logic controller with V_{dc} and V_{ref}, the reference value of the dc bus voltage. The obtained d-q axis components generate voltage command signal [4]. By using Fourier magnitude block, voltage magnitude and angle is calculated from the obtained signal. These values are fed to the developed code and compared with the repeating sequence. Then the time durations T_1, T_2 and T_0, the on-time of V_1, V_2 and V_0 are calculated [5]. The generated switching actions are applied to the APF and power balancing of the filter takes place.

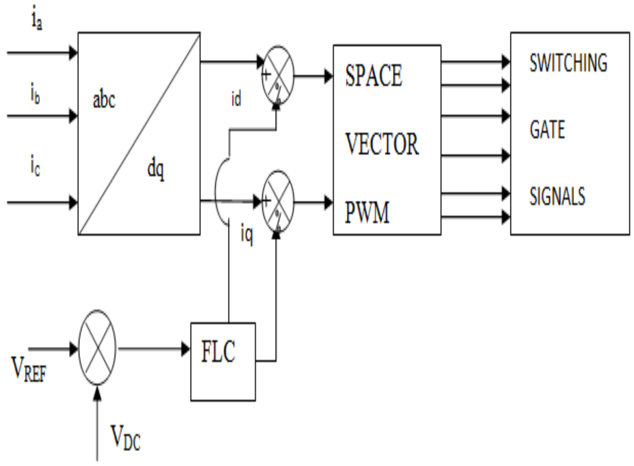

Fig.4 Control block diagram of Fuzzy based SVPWM

5.2 Fuzzy logic controller

In the Fuzzy logic controller, 1) a generalized integrator control unit and 2) a fuzzy adjustor unit control circuits are used. The first control circuit is used for dividing frequency integral control, to ignore the influence of magnitude and phase, while fuzzy arithmetic is used to timely adjust the PI coefficients. Since the main objective of this scheme is to obtain a minimum steady-state error, the harmonic reference signal is set to zero. First, supply harmonic current is detected. Then, the expectation control signal of the inverter is revealed by the entire control units. The system stability is achieved by a p-controller, and the exact dynamic state is obtained by the integral controller. To adjust the parameters of p-control and integral control, a fuzzy adjustor is also used. So that the harmonic tracking current controller can reduces the tracking error of the harmonic compensation current.

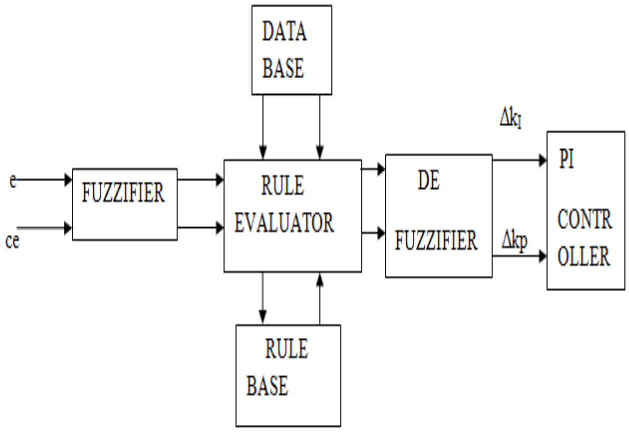

Fig.5 Block diagram of Fuzzy Logic Controller

Once the fuzzy controller were developed and incorporated into the simulated system, the simulation performances helped in the iteration of the controllers and best adaptive controller to the linear and non linear systems. Fuzzy controller main parts are evaluation and control rules from the rule base and data base is called fuzzifier and defuzzifier is takes highest MF component. The FLC having different membership functions (M.Fs) to analyze the performance of instantaneous real active and reactive current (id–iq) control strategy for extracting reference currents of SHAF under different source voltage conditions. PWM pattern generation based on carrier less hysteresis current control is used for quick response. In addition, the i_d–i_q method is used for obtaining reference currents in the system, because in this strategy, angle 'u' is calculated directly from the main voltages and enables operation to be frequency independent; thereby, this technique avoids a large number of synchronization problems.

The fuzzy inference system (FIS) in the fuzzy logic toolbox [5], it consists of FIS editor, Member ship Function (MF) editor, Rule editor, Rule viewer, Surface viewer. Membership functions are symmetrical or asymmetrical; it is multi dimensional curves and forming hyper surface. In Fig. 6.1and Fig.6.2, M.F editor of k_p and k_i having two inputs (error, cerror) and single output curves (K_p and K_i). The M.F editor is used to define the shapes of all the M.Fs associated with each variable. The rule editor is used for editing the list of control rules that define the behavior of the system. In the present model 49 rules are developed in below. Fig.7.1 and Fig.7.2 shows rule view of K_p and K_i. Fig.8.1 and fig.8.2 shows hyper surface view of K_p and K_i are generally obtained from control rule.

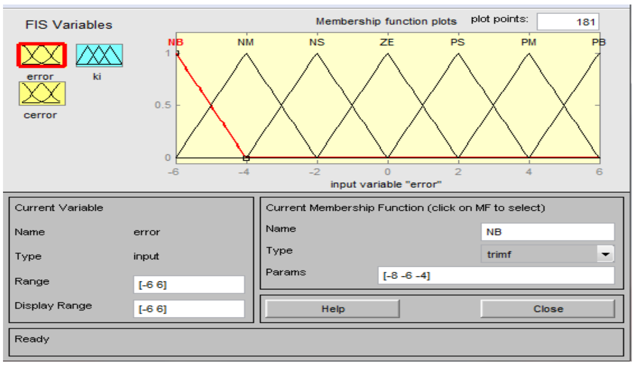

Fig. 6.1 MF editor for k_p

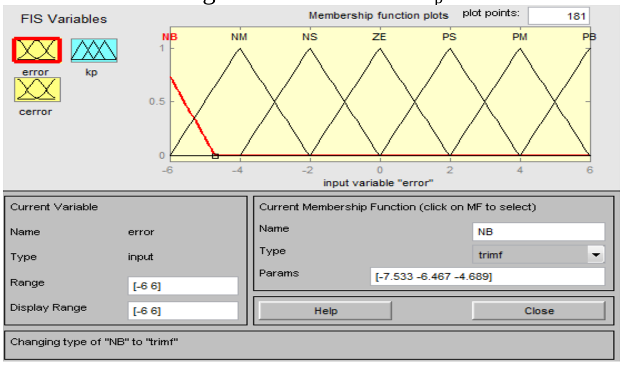

Fig.6.2 MF editor for k_i

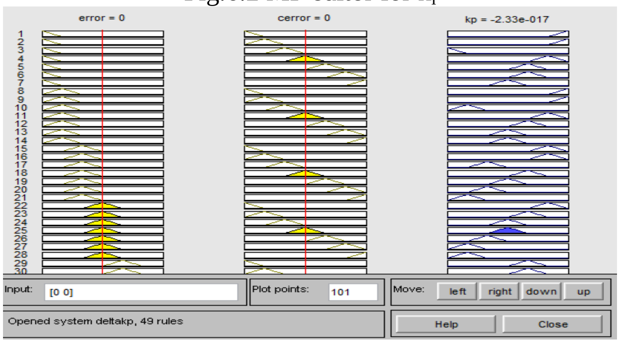

Fig.7.1 Rule view for K_p

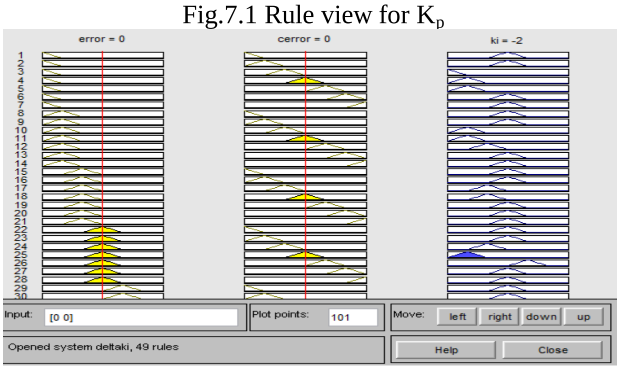

Fig. 7.2 Rule view for k_i

The fuzzy control rule design involves defining rules that relates to the output model properties. For designing the control rule base for tuning ΔKp and $\Delta K_{i,}$ the following important factors have been taken into account.

1) For large values of /e/, a large Δk_p is required, and for small values of /e/,a small Δk_p is required.

2) For e, e_c >0, a large Δk_p is required and for e, e_c >0 a small Δk_p is required.

3) For large values of /e/ and /e_c/, ΔK_p is set to zero, which can avoid control saturation.

4) For small values of /e/, ΔK_p is effective ,and Δk_p is larger when /e/ is smaller ,which is better to decrease the steady state error. So the tuning rule of ΔK_p and ΔK_i can be obtained as given Table 1 and Table 2.

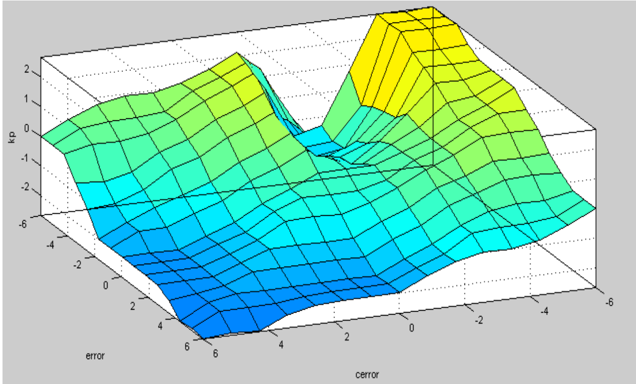

Fig .8.1 Hyper surface view of kp

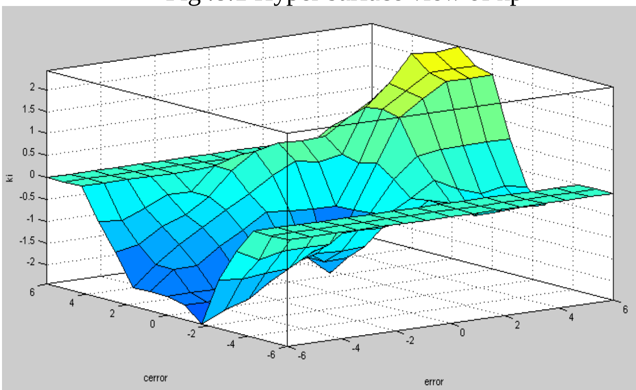

Fig.8.2 Hyper surface view of ki

Table 1 Adjusting parameters of ΔKp

ΔKp		e_c						
		NB	NM	NS	O	PS	PM	PB
e	NB	PB	PB	NB	PM	PS	PS	0
	NM	PB	PB	NM	PM	PS	0	0
	NS	PM	PM	NS	PS	0	NS	NM
	0	PM	PS	0	0	NS	NM	NM
	PS	PS	PS	0	NS	NS	NM	NM
	PM	0	0	NS	NM	NM	NM	NB
	PB	0	NS	NS	NM	NM	NB	NB

Table 2 Adjusting parameters of ΔKi

ΔK_i		e_c						
		NB	NM	NS	O	PS	PM	PB
e	NB	0	0	NB	NM	NM	0	0
	NM	0	0	NM	NM	NS	0	0
	NS	0	0	NS	NS	0	0	0
	0	0	0	NS	NM	PS	0	0
	PS	0	0	0	PS	PS	0	0
	PM	0	0	PS	PM	PM	0	0
	PB	0	0	NS	PM	PB	0	0

6 Results and Discussions

The simulation model of Hybrid active power filter for non linear load is shown in Fig.1. For an input supply voltage of 230V (rms) and switching frequency of 5kHz, the simulation results with PID controlled SVPWM and fuzzy controlled SVPWM hybrid active filter are shown. Table.3 shows parameter values required for circuit configuration shown in Fig.2.

Table.3 Parameter values

<table>
<tr><th>System parameters</th><th colspan="4">Values of parameters</th></tr>
<tr><td>Supply system</td><td colspan="4">230 V (rms), 50 Hz, three-phase supply</td></tr>
<tr><td rowspan="5">Passive</td><td></td><td>L/mH</td><td>C/μF</td><td>Q</td></tr>
<tr><td>Output filter</td><td>0.2</td><td>60</td><td></td></tr>
<tr><td>11th turned filter</td><td>1.77</td><td>49.75</td><td>50</td></tr>
<tr><td>13th turned filter</td><td>1.37</td><td>44.76</td><td>50</td></tr>
<tr><td>6th turned filter</td><td>14.75</td><td>C_F:19.65, C_I:690</td><td></td></tr>
<tr><td>APF</td><td colspan="4">C_{dc}=1000μf, Vref = 750V,C_f = 24μf, L_f = 30 mH</td></tr>
</table>

Fig.9. shows the simulation results of hybrid active power filter when PID controlled SVPWM technique is considered for generating the required switching pulses for the operation of the active filter. It shows the simulation waveforms of source voltage, load current after compensation and source current after compensation. From the figures, it can be observed that there is some asymmetry during the initial conditions in the source voltage and source current waveforms, whereas the load current waveforms are distorted in nature.Fig.10 shows the simulation results of hybrid active power filter when fuzzy controlled SVPWM technique is considered for generating the required switching pulses for the operation of the active filter. It shows the simulation waveforms of source voltage, load current and source current after compensation. From the figures, it can be observed that under nonlinear load condition the magnitude of three phase source voltage, source current and load current are made equal, made in phase with each other and also shows that the reduction of harmonics is better.

The simulation of harmonic spectrum of hybrid active power filter when PI based SVPWM controller is considered. Fig.11.1shows the harmonic spectrum of the load current after compensation is done. Fig.11.2. shows the harmonic spectrum of the source current after compensation is done. The harmonic spectrum of the load current and source current shows that the %THD is reduced from 21.78 to 2.72. It also observed that the magnitude of the 5th, 7th, 11th and 13th harmonics is large enough in source current harmonic spectrum.

The simulation of harmonic spectrum of hybrid active power filters when fuzzy based SVPWM controller is considered. Fig.12.1. shows the harmonic spectrum of the load current after compensation is done. Fig.12.2. shows the harmonic spectrum of the source current after compensation is done. The harmonic spectrum of the load current and source current shows that the %THD is reduced 1.57 in both. It also observed that the magnitude of the 5th, 7th, 11th and 13th harmonics are evidently reduced by fuzzy based SVPWM controller based hybrid active power filter when compared to PI based SVPWM technique.

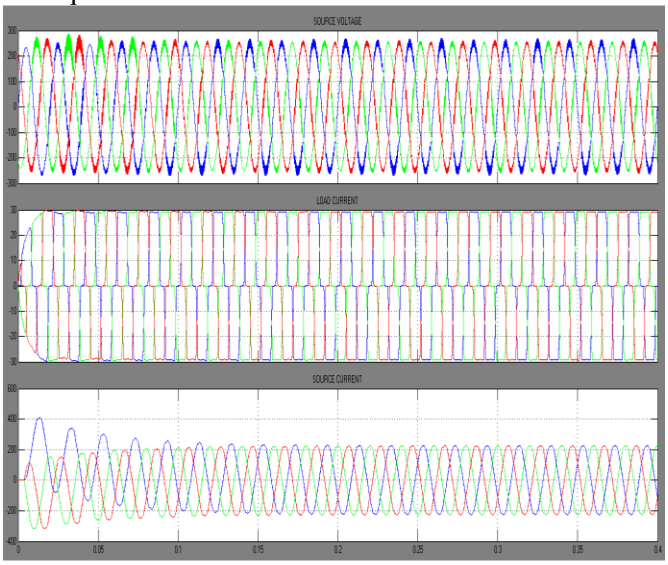

Fig. 9 Wave Forms of PID based SVPWM

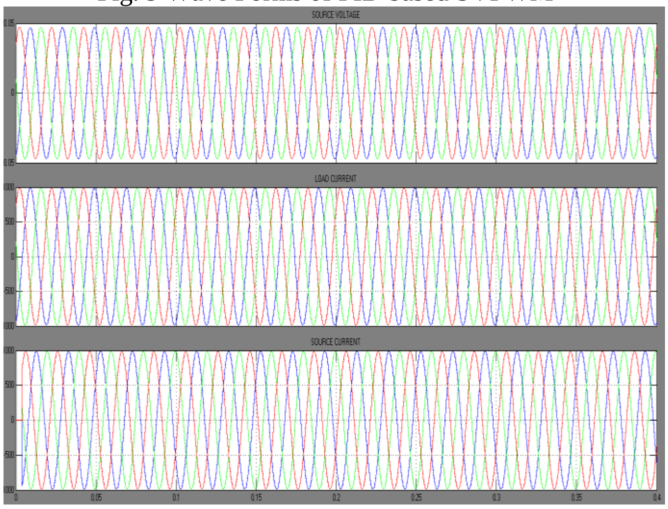

Fig. 10 Wave Forms of Fuzzy based SVPWM

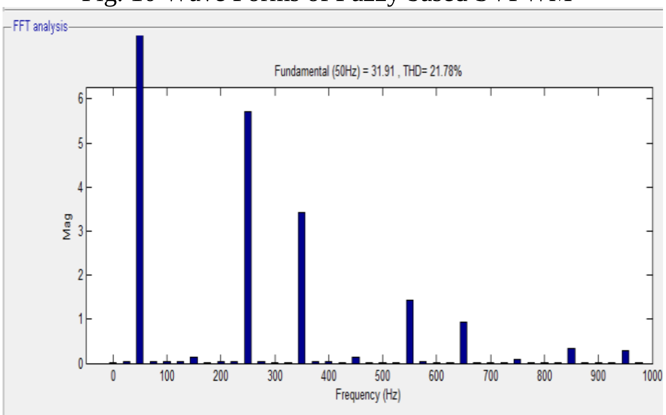

Fig.11.1 Load current Harmonic for PID based SVPWM

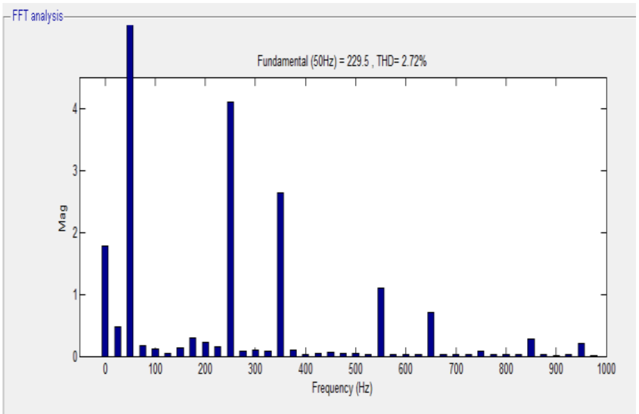

Fig.11.2 Source current harmonic of PID based SVPWM

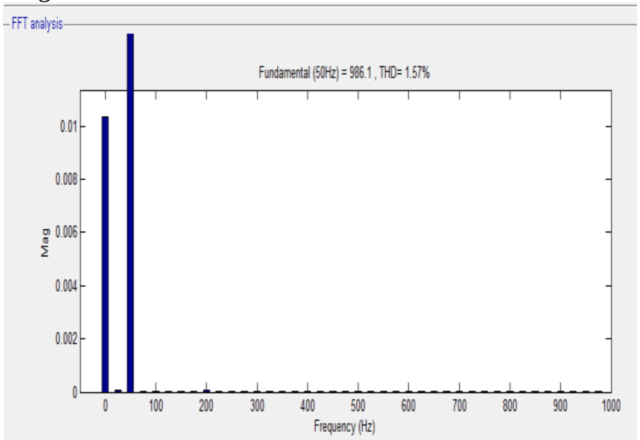

Fig12.1 Load current Harmonic for Fuzzy SVPWM

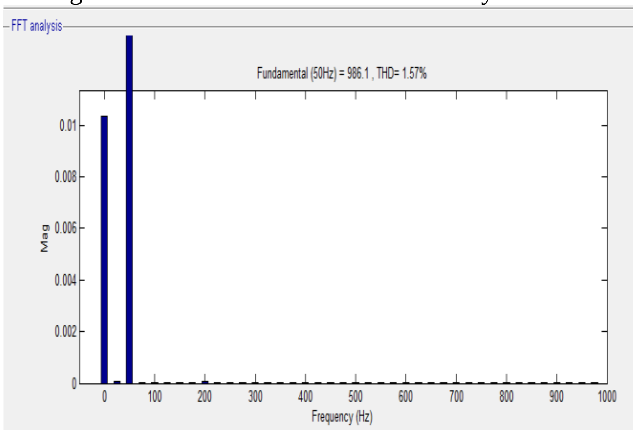

Fig.12 .2 Source current harmonic of Fuzzy SVPWM

7 Conclusion

In this paper, in detailed analysis of the hybrid active power filter using fuzzy logic based SVPWM control methodology is explained. This method requires a very simple algorithm, which can be able to compensate the harmonic content from both source as well as load current efficiently. Simulations are carried out in MATLAB / Simulink to obtain the performance of proposed filter. From the simulation results it is observed that %THD is reduced from 21.78 to 2.72 with hybrid active power filter when PI based SVPWM controller is considered and the harmonic spectrum of the load current and source current shows that the %THD is reduced 1.57 in both currents when fuzzy based SVPWM controller is considered. So the proposed controlled filters such as PI based SVPWM and fuzzy based SVPWM controlled hybrid active power filters can be able to reduce the total harmonic distortion efficiently. Whereas, among the two, fuzzy based SVPWM controlled hybrid active filter not only functioning on source side but also functioning efficiently on load side to made phases with each other, to made magnitudes equal and to reduce the total harmonic distortion.

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