# PI with Fuzzy Logic Controller based Active Power Line Conditioners

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**Abstract –This paper presents a proportional integrator (PI) in conjunction with Fuzzy Logic controller (FLC) based Shunt active power line conditioners (APLC) for power quality improvements. The objective is to investigate different control methodologies for real time compensation of current harmonics and reactive power due to non-linear loads at various power conditions. The compensation process includes controlling dc-bus capacitor voltage of the inverter and estimating peak reference current by using PI with fuzzy logic controller. The reference currents are extracted from unit sine vector multiplied with estimated peak reference current. The voltage source inverter switching signals are obtained through hysteresis current controller (HCC). The performance of shunt APLC is evaluated through Matlab/Simulink simulation under different steady state and transient conditions using PI, FLC and PI in conjunction with FLC. The results demonstrate that combination of PI with FLC is a better solution that reduces the settling time of the dc-bus capacitor and suppresses current harmonics in the loads.**

**Keywords – Shunt Active Power Line Conditioners (APLC), PI controller, Fuzzy Logic Controller (FLC), Harmonics, Hysteresis Current Controller (HCC).**

## I. INTRODUCTION

The ac power supply feeds different kind of linear and non-linear loads. The non-linear loads produce harmonics and reactive power related problems [1]. This harmonics and reactive power cause poor power factor and distort the supply voltage at the point of common coupling (PCC). This distortion is mainly induced due to the line impedance or distribution transformer leakage inductance. The current harmonics create problems in power systems such as malfunctions in sensitive equipment, overvoltage by resonance and harmonic voltage drop across the network impedance; that result in poor power factor [2]. Traditionally these problems are solved by passive filters. But these passive filters introduce tuning problems, resonance, and are large in size and it's also limited to few harmonics [3-4]. Recently active power-line conditioners (APLC) are developed to compensate the current harmonics and reactive power simultaneously in addition to power factor correction [5]. APLC keeps the mains current balanced after compensation regardless of either the load is non-linear and/or unbalanced [6]. The shunt APLC can be developed with current source inverter or voltage source inverter. Generally the voltage source inverter (VSI) is preferred for the shunt active power circuit due to lower losses in the dc-side capacitor [7].

The controller is the most important part of the APLC and currently lot of research is being conducted in this area [8-10]. Conventional PI and proportional integral derivative (PID) controllers have been used to estimate the peak reference currents and control the dc side capacitor voltage of the inverter. Most of the active filter systems use PI-controller for maintaining the dc side capacitor voltage [5-11]. When the source supplies a non-linear or reactive load, it is expected to supply only the active fundamental component of the load current and the compensator supplies the harmonic/reactive component. The outer capacitor voltage loop will try to maintain the capacitor voltage nearly constant which is also a mandatory condition for the successful operation of the APLC. The system losses are provided by the source in steady state. The compensator supplies the harmonic power, which manifests itself only on the reactive component of power. In the transient conditions the load changes are reflected in the dc capacitor voltage as an increase (or decrease) as capacitor absorbs (or delivers) the excess (or deficit) power. This conservation of energy philosophy is used to obtain the reference current for compensator in this method. The perturbations in the capacitor voltage are related to the perturbations in the average power drawn by the non-linear load. This property is utilized which facilitates extracting compensator reference and maintains capacitor voltage. However, the conventional PI controller requires precise linear mathematical model of the system, which is difficult to obtain under parameter variations and non-linear load disturbances. Another drawback of the system is that the proportional and integral gains are chosen heuristically [12-13]. Recently, fuzzy logic controllers (FLC) are used in power electronic systems and active power filter applications [14-18]. In the present work we combine PI and FLC techniques for efficient power line conditioning. This controller can handle non-linearity and is more robust.

This research paper presents a novel controller that uses PI in conjunction with Fuzzy logic controller for active power line conditioner. The proposed PI with fuzzy logic controller is used to estimate peak reference current besides maintaining the DC side capacitor voltage of the inverter nearly constant. Hysteresis current controller is used to generate the switching signals for switches in the inverter. The shunt APLC is investigated under different steady state and transient conditions using PI, FLC and PI in conjunction with FLC and is found to be effective for compensation; the proposed PI with FLC reduces ripples in the dc side capacitor.

## II. DESIGN OF SHUNT APLC

The basic compensation principle of shunt APLC is to draw/supply compensating current, from/to the distributor system such that it cancels current harmonics on the

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source side and makes the source current sinusoidal and is in phase with the source voltage. The active power filter is implemented with pulse width modulated (PWM) current controlled voltage source inverter (VSI). The three phase APLC consists of six power transistors with freewheeling diodes, a dc capacitor, RL filter, compensation controller (PI or FLC or PI in conjunction with FLC) and gate signal generator (hysteresis current controller) as shown in the Fig 1. These PI and Fuzzy logic controller algorithm is used to extract the desired reference current from the load current. The hysteresis current controller is employed to generate the switching signals for driving switches in the VSI. The inductive-filter suppresses the harmonics caused by the switching operation of the IGBT inverter. This inductive-filter provides smoothing and isolation for high frequency components. The current wave shape is limited by the switching frequency of the voltage source inverter.

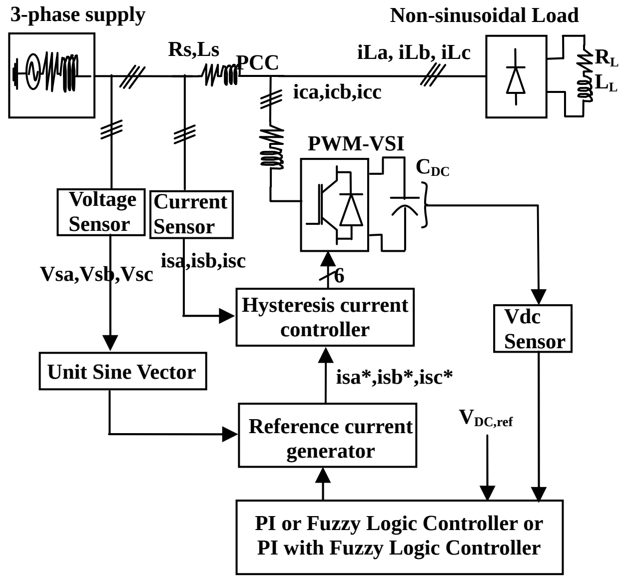



Fig. 1 structure of Shunt APLC system

The three phase source is connected to a diode rectifier (non-linear) load. This nonlinear load current contains fundamental component and higher order of harmonic current components. For this system, the instantaneous load current can be written as follows

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \Phi_n)$$
$$= I_1 \sin(\omega t + \Phi_1) + \left( \sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \right) \quad (1)$$

The load power comprises fundamental power and reactive power including harmonic power. The instantaneous load power can be written as

$$p_L(t) = i_s(t) * v_s(t)$$
$$= V_m \sin^2 \omega t * \cos\phi_1 + V_m I_1 \sin\omega t * \cos\omega t * \sin\phi_1$$
$$+ V_m \sin\omega t * \left( \sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \right)$$
$$= p_f(t) + p_r(t) + p_h(t) \quad (2)$$

Here $p_f(t)$ is the fundamental component of power, $p_r(t)$ is the reactive power and $p_h(t)$ represents harmonic power. From this equation only the real (fundamental) power drawn by the load is

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos\phi_1 = v_s(t) * i_s(t) \quad (3)$$

The source current drawn from the mains after compensation should be sinusoidal; this is represented as

$$i_s(t) = p_f(t) / v_s(t) = I_1 \cos\phi_1 \sin\omega t = I_{max} \sin\omega t \quad (4)$$

If the active power line conditioner provides the total reactive and harmonic power, source current $i_s(t)$ will be in phase with the utility voltage and would be sinusoidal. At this time, the active filter must provide the compensation current:

$$i_c(t) = i_L(t) - i_s(t) \quad (5)$$

APLC estimates the fundamental from the load current and compensates for the harmonic and reactive component.

*Design of DC side capacitor:*

The DC-side capacitor voltage is maintained constant with small ripples in steady state. It acts as energy storage element to supply real power (difference between load and source) during the transient period as already presented in the introduction. The real/reactive power injection results in the ripple voltage of DC capacitor. The selection of $C_{DC}$ should be such that it facilitates reducing voltage ripple.

*Design of filter inductance $L_C$ and reference voltage:*

The design of the filter inductance ($L_C$) and reference voltage ($V_{DC,ref}$) components is based on the following assumption; (1) The ac source voltage is sinusoidal (2) To design $L_C$ the ac-side line current distortion is assumed to be *5%*. (3) Fixed capability of reactive power compensation of the APLC. (4) The PWM-inverter is assumed to operate in the linear modulation index ($i.e. 0 \le m_a \le 1$) . The desired reference voltage is compared with actual dc-bus capacitor voltage for reducing the ripples in transient conditions.

## III. Proposed Control Strategies

The proposed control strategy consists of extracting reference current and hysteresis current controller for IGBT inverter. The reference current is extracted from the nonlinear load current. The magnitude of the reference current is estimated by PI or FLC or PI with fuzzy logic controller.

*A) Reference current control strategy:*

The reference current generation is based on estimated peak reference currents that are multiplied with unit sine vector outputs. The proposed PI with fuzzy logic controller is used to estimate the peak reference current.

*A.1) Unit sine vector:*

The voltage source is converted to the unit current(s) while corresponding phase angles are maintained. According the ohms law the current is inversely proportional to the resistance $\left(i = V / R\right)$. Unit sine vector is derived from the supply voltage template.

$$i_a = \sin \omega t, i_b = \sin(\omega t - 120^0),\ i_c = \sin(\omega t + 120^0) \qquad (6)$$

The amplitude of the sine current is unit or 1 volt and frequency same source voltage and it is also in the same phase. This unit current multiplied with peak value of control output generates reference current.

*A.2) PI with Fuzzy controller:*

Figure 2 shows the block diagram of the proposed proportional integral (PI) control with fuzzy logic controller scheme for APLC. The DC-side capacitor voltage is sensed and is compared with a reference voltage signal and generates error signal. The error signal $e = V_{dc,ref} - V_{dc}$ at the $n^{th}$ sampling instant is used as input to the PI-controller.

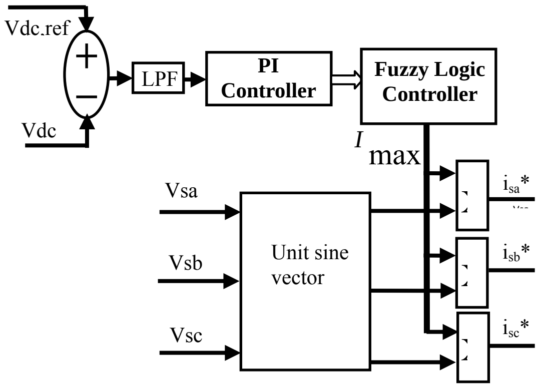



Fig. 2 PI with fuzzy logic Controller block diagram

The error signal passes through Butterworth low pass filter (LPF) that suppresses higher frequency components and allows only fundamental components. PI-controller estimates the magnitude of peak reference current $I_{\max}$ and controls the dc-side capacitor voltage of the inverter. Its transfer function is

$$H(s) = K_P(s) + \frac{K_I}{s} \qquad (7)$$

where, [ $K_P$ =0.7] is the proportional constant that determines the dynamic response of the DC-side voltage and [ $K_I$ =23] is the integration constant that determines it's settling time. The PI controller output contains certain ripples, so we need another processing unit to reduce this ripple; the FLC is connected together with PI controller for reducing the ripples.

Fuzzy logic controller block diagram shown in Fig 3, the transition between membership and non membership functions can be gradual. The PI controller output error is used as inputs for FLC. The linguistic variables are error $E(n)$, change of error $CE(n)$ and output $I_{\max}$.

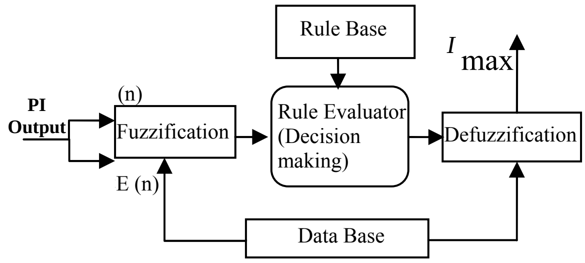
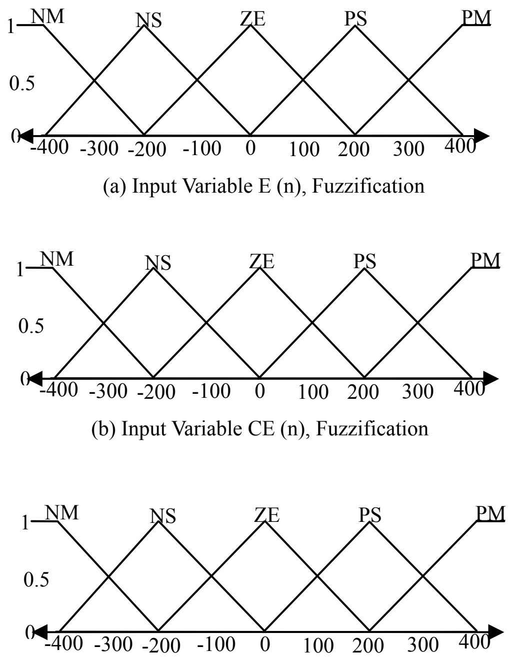



Fig. 3 fuzzy logic Control block diagram

<u>*Fuzzification:*</u>

In a control system, error between reference and output can be labeled as zero (ZE), positive small (PS), negative small (NS), positive medium (PM), negative medium (NM). The process involves converting a numerical variable to a linguistic variable; five-sets triangular membership function are developed for the fuzzification as shown in Fig 4.




(c) Output Variable (Imax), DeFuzzification

Fig. 4 FLC membership functions (a) the input variables e (n) (b) change of error ce (n) and (c) output variable defuzzification

<u>*Rule Elevator:*</u>

The basic fuzzy set operations needed for evaluation of fuzzy rules are $AND(\cap)$, $OR(\cup)$ and $NOT(-)$

$AND$ -Intersection: $\mu_{A\cap B} = \min[\mu_A(X), \mu_B(x)]$

$OR$ -Union: $\mu_{A\cup B} = \max[\mu_A(X), \mu_B(x)]$

$NOT$ -Complement: $\mu_A = 1 - \mu_A(x)$

<u>*Defuzzification:*</u>

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

<u>*Database:*</u>

The Database stores the definition of the membership function required by fuzzifier and defuzzifier

<u>*Rule Base:*</u>

The Rule base stores the linguistic control rules required by rule evaluator, the 25-rules used in this paper are presented in table 1.

**Table 1 Rule base table**

| e(n) / ce(n) | NM | NS | ZE | PS | PM |
|---|---|---|---|---|---|
| NM | NM | NM | NM | NS | ZE |
| NS | NM | NM | NS | ZE | PS |
| ZE | NM | NS | ZE | PS | PM |
| PS | NS | ZE | PS | PM | PM |
| PM | ZE | PS | PM | PM | PM |

The desired reference source currents after compensation should be sinusoidal and it can be given as

$$i_{sa}* = I_{\max} \sin \omega t \quad (8)$$

$$i_{sb}* = I_{\max} \sin(\omega t - 120^0) \quad (9)$$

$$i_{sc}* = I_{\max} \sin(\omega t + 120^0) \quad (10)$$

where $I_{\max}$ the amplitude of the desired source current and the phase angle can be obtained from the source voltages using unit sine vector. The reference currents $(i_{sa}*, i_{sb}*, i_{sc}*)$ are compared with actual source currents $(i_{sa}, i_{sb}, i_{sc})$ to generate switching signals for PWM-inverter using hysteresis current controller.

*B) Hysteresis Band Current Control:*

There are various current control methods proposed for APLC conFigurations; but in terms of faster current controllability and easy implementation, the hysteresis current control method scores over other current control techniques.

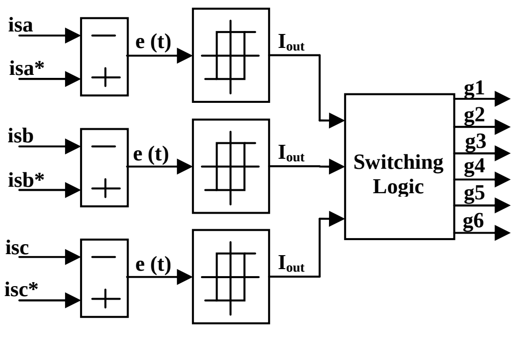



*Fig 5 Structure of hysteresis current controller*

Hysteresis band current control demonstrates characteristics like robustness, excellent dynamics and fastest control with minimum hardware. For the PWM-voltage source inverter; hysteresis current controllers are conFigured independently for each phase. Each current controller directly generates the switching signal of the three (a, b, c ) phases shown in Fig 5. In the case of positive input current, if the error current $e(t)$ between the desired reference current $i_{ref}(t)$ and the actual source current $i_{actual}(t)$ exceeds the upper hysteresis band limit $(+h)$, the upper switch of the inverter arm is become OFF and the lower switch is become ON. As a result, the current starts to decrease. If the error current $e(t)$ crosses the lower limit of the hysteresis band (-h), the lower switch of the inverter arm is become OFF and the upper switch is become ON. As a result, the current gets back into the hysteresis band and the cycle repeats.

$$S = \begin{cases} 0 & if\ i_{actual}(t) > i_{ref}(t) + h \\ 1 & if\ i_{actual}(t) < i_{ref}(t) - h \end{cases} \quad (11)$$

Here the hysteresis band limit used is h=0.5. The range of the error signal $e(t)$ directly controls the amount of ripple voltage in the output current from the PWM-VSI.

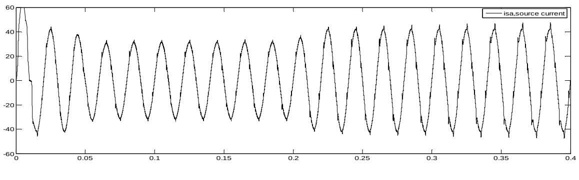
## IV. Simulation Result and Analysis

The SIMULINK toolbox in the MATLAB is used to model and test the system under steady state and transient conditions using PI, Fuzzy logic and combination of PI and fuzzy logic controllers. The system parameter values are; source voltage (Vs) is 230 Vrms, System frequency (f) is 50 Hz, Source impedance $R_S$, $L_S$ is 1 Ω; 0.2 mH respectively, Filter impedance $R_c$, $L_c$ is 1 Ω; 2.5 mH, Load impedance $R_L$, $L_L$ of diode rectifier RL load in steady state: 20 Ω; 200 mH and in transient: 10 Ω; 100 mH respectively, DC link capacitance ($C_{DC}$) is 1600μF, Reference Voltage ($V_{DC}$) is 400V and Power devices are IGBT with a freewheeling diode in anti parallel.

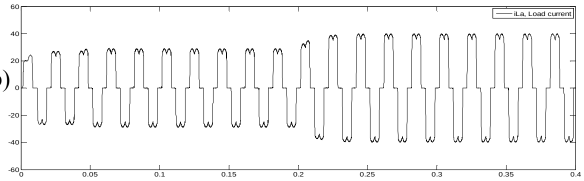
*PI with Fuzzy controller:*

PI with Fuzzy logic controller based APLC system comprises a three-phase source, a nonlinear load (six pulse diode rectifier RL load) and a PWM voltage source inverter with a dc capacitor on dc side. The simulation of the source current after compensation is presented in Fig. 6 (a) that indicates that the current becomes sinusoidal. The load current is shown in 6 (b). The actual reference current for phase is shown in Fig. 6(c). This wave is obtained from our proposed controller. The APLC supplies the compensating current that is shown in Fig. 6(d). The current after compensation is as shown in (a) which would have taken a shape as shown in (b) without APLC. It is clearly visible that this waveform is sinusoidal with some high frequency ripples. We have additionally achieved power factor correction as shown in Fig. 6(e), phase (a) voltage and current are in phase.

a)



b)



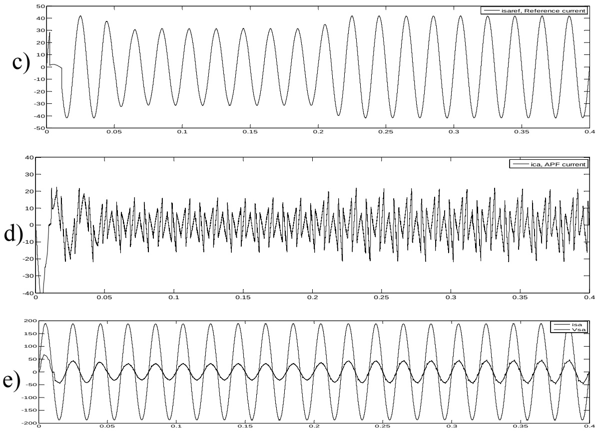


Fig. 6 PI with Fuzzy logic controller based simulation results for three-phase active-power-filter under the steady state condition (a) Source current after APLC, (b) Load currents, (c)Reference currents by the Fuzzy logic algorithm, (d) Compensation current by APLC and (e) unity power factor

First we conducted simulation ( time T=0 to T=0.4s ) with rectifier load with RL at output with values 20 ohms and 200 mH respectively and then RL load is suddenly changed to 10 ohms and 100 mH for transient condition. The transient simulation waveforms are plotted in a similar manner and are shown in Fig 7.

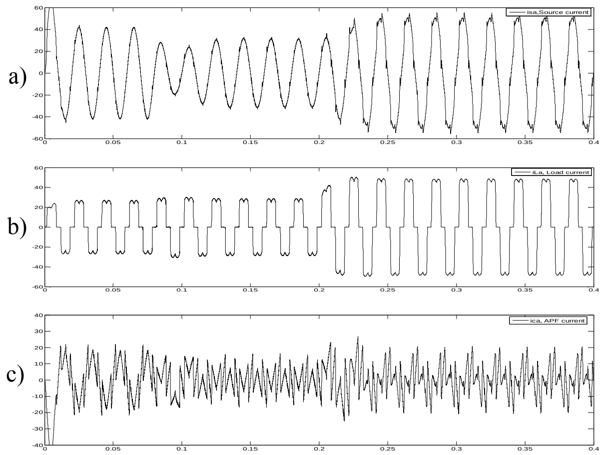
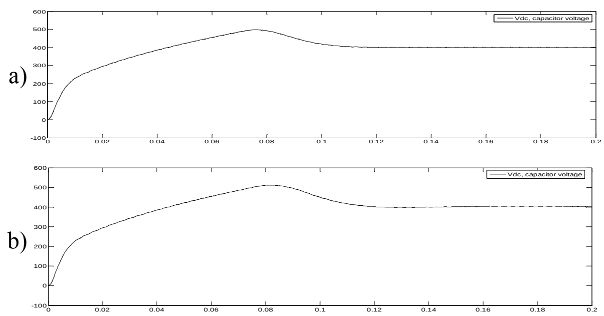


Fig. 7 PI with Fuzzy logic controller based simulation results for three-phase active-power-filter under the transient condition (a) Source current after APLC, (b) Load currents and (c) Compensation current by APLC

The DC side capacitor voltage is effectively controlled by the PI or FLC and/or combination of PI with FLC shown in Fig 8. It is observed that settling time is quite fast. The combination of PI with FLC takes least settling time and has small ripples compared to individual PI and FLC controllers.



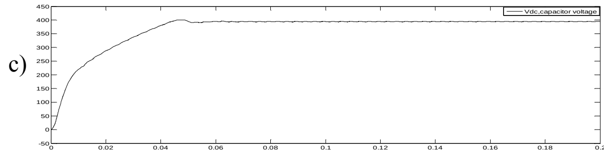


Fig. 8 simulation results for 3-phase APLC under steady state condition; waveform of DC side capacitor voltage controlled by (a) PI controller (b) FLC controller (c) PI with FLC controller

The dc-side capacitor voltage settling time in transient and steady state conditions using different controller are presented in table 2

**Table 2 Vdc settling time using PI, FLC and PI with FLC controller**

| Condition | PI controller | Fuzzy controller | PI with Fuzzy Controller |
|---|---|---|---|
| Steady state | 0.12s | 0.11s | 0.065s |
| Transient | 0.13s | 0.12s | 0.060s |

The PI with fuzzy logic controller based APLC system effectively suppresses the harmonics, compensates reactive power and improves power factor. Real power in watts (W) and reactive power in volt-amperes (VAR) are measured under steady state and transient condition and are presented in table 3

**Table 3 Active and Reactive power measurement using PI, FLC and PI with FLC controller**

| Load Condition | Without APLC | Power measurement With APLC | |
|---|---|---|---|
| Steady state | P=3.907 kW Q=219 VAR | PI | P=4.039 kW Q=81 VAR |
| | | Fuzzy | P=4.033 kW Q=72 VAR |
| | | PI with Fuzzy | P=4.057 kW Q=75 VAR |
| Transient | P=4.847 kW Q=268 VAR | PI | P=4.97 kW Q=41 VAR |
| | | Fuzzy | P=4.98 kW Q=40 VAR |
| | | PI with Fuzzy | P=5.17 kW Q=36 VAR |

The Fourier analysis of the source current is done to find magnitudes of different harmonic components and is shown in Fig 9.

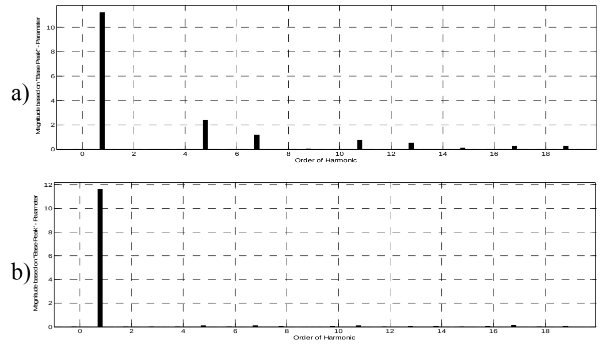


Fig. 9 PI with FLC-controller based harmonics measured with respect to the magnitude under the steady state condition (a) Source current without APLC, (b) source currents with active power line conditioners

The total harmonic distortion (THD) is computed. PI with FLC based shunt APLC indicates that THD of the source current is less than 5% after compensation that is in compliance with IEEE-519 standards harmonic, shown in table 4

**Table 4 THD measurement using PI, FLC and PI with FLC controller**

| Load Condition | Without APLC | THD measurement With APLC | | |
|---|---|---|---|---|
| | | PI controller | Fuzzy controller | PI with Fuzzy logic Controller |
| Steady state | 26.28% | 3.10% | 2.87% | 2.52% |
| Transient | 26.37% | 3.18% | 2.79% | 2.32% |

## V. Conclusion

Proportional-Integral in conjunction with fuzzy logic controller based Shunt APLC performs quite well and it compensates both harmonic currents and reactive power. Simulation results demonstrate that source current after compensation is sinusoidal and is in phase with source voltage. PI with FLC facilitates reduction of ripples in dc-side capacitor of the inverter. The PI, FLC and PI with FLC-controllers are investigated under both steady state and transient conditions and it is observed that PI with FLC-controllers provides superior performance in terms of compensation and settling time compared to other methods. The PI with FLC based APLC system is in compliance with the IEEE-519 standards harmonics.

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