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PI with Fuzzy Logic Controller based APLC for compensating harmonic and reactive power

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Abstract— **this article explores design and analysis of proportional integrator (PI) along with Fuzzy Logic controller (FLC) based Shunt active power line conditioners (APLC) for compensating reactive power and harmonic currents drawn by the load. The aim is to study different control strategies for real time compensating current harmonics at different power conditions. The compensation process is based on calculation of unit sine vector and reduces the dc capacitor ripple voltage of the PWM-VSI by using PI with fuzzy logic controller. The switching is done according to gating signals obtained from hysteresis band current controller and capacitor voltage is continuously maintained constant. The shunt APLC is investigated through Matlab/Simulink simulation under different steady state and transient conditions using PI, FLC and PI with FLC. The results demonstrate that combination of PI with FLC is a better solution that reduces the settling time of the dc capacitor and suppresses harmonics in the load current(s).**

***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 type of loads produces harmonics [1]. The reactive power and harmonics cause poor power factor and distort the supply voltage at the common coupling point. This distortion is mainly induced by the line impedance or the distribution transformer leakage inductance. Passive L-C filters were used to compensate the lagging power factor of the reactive load, but due to the drawbacks as resonance, size, weight, etc., the alternative solution came up, an APLC that provides an effective solution for harmonic elimination and reactive power compensation [2].

The controller is the heart of the active power filter and a lot of research is being conducted in recent years. Conventional PI voltage and current controllers have been used to control the harmonic current and dc voltage of the shunt APLC. Recently, fuzzy logic controllers (FLC) are used in power electronic system and drive applications [3]. This paper combines these two techniques for efficient line conditioners. APLCs are inverter circuits, comprising active devices such as semiconductor switches can be controlled as harmonic current or voltage generators. Different topologies and control techniques have been proposed for their implementation. APFs are superior to passive filters in terms of filtering characteristics and improve the system stability by removing resonance related problems [4]. In particular, recent remarkable progress in the capacity and switching speed of power semiconductor devices such as insulated-gate bipolar transistors (IGBTs) has spurred interest in active filters for power conditioning [3-6].

This research paper describes of a novel controller that uses PI along with Fuzzy logic controller for APLC. This computed sensing source voltage and current is activated unit sine vector calculation to generate reference currents. The PWM-VSI inverter ripple voltage (dc side capacitor) is reduced using Proportional Integrated controller as well as Fuzzy logic controller. A hysteresis current controller generates switching signals for the APLC to follow the reference currents within specified band-limits. The shunt APLC is investigated under different steady state and transient conditions and found to be effective for power factor correction and reduces ripple voltage with the proposed PI with Fuzzy logic controller.

II. DESIGN OF SHUNT ACTIVE POWER LINE CONDITIONERS

The basic compensation principle of shunt APLC or active filter is controlled to draw/supply compensating current, from/to the utility. So that it cancels a current harmonic on the AC side and makes the source current in phase with the source voltage. A shunt active filter is connected to the supply through filter inductances and operates as a closed loop controlled current source shown in fig 1. The output voltage of the inverter is controlled with respect to the voltage at the point of common coupling (PCC). The design of APLC containing the following parameters;

Source current:
The instantaneous current supplied by the source, before compensation and it can be written as

$$i_s(t) = i_L(t) - i_c(t) \tag{1}$$

Source voltage is given by

$$v_s(t) = V_m \sin \omega t \tag{2}$$

If a nonlinear load is applied, then the load current will have a fundamental component and harmonic components, which can be represented as

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \Phi_n) \tag{3}$$

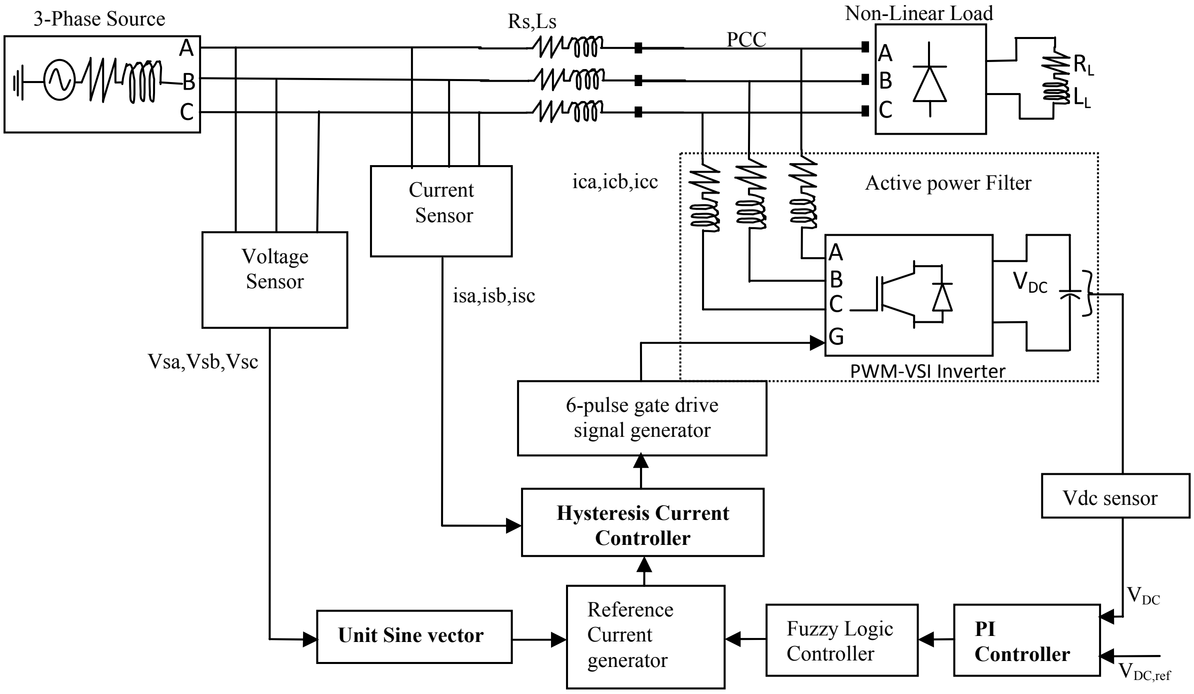


Fig 1 PI with Fuzzy Logic Controller based shunt Active Power Line Conditioners system

The instantaneous load power can be written as

$$\begin{aligned} p_L(t) &= i_s(t) * v_s(t) \\ &= V_m \sin^2 \omega t * \cos\phi_1 + V_m I_1 \sin\omega t * \cos\omega t * \sin\phi_1 \\ &\quad + V_m \sin\omega t * \left(\sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \right) \\ &= p_f(t) + p_r(t) + p_h(t) \end{aligned} \qquad (4)$$

From the equation the load current should contain real or fundamental power, reactive power and harmonic power. The real power drawn by the load is

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos\phi_1 = v_s(t) * i_s(t) \qquad (5)$$

From this equation the source current supplied by the source, after compensation is

$$i_s(t) = \frac{p_f(t)}{v_s(t)} = I_1 \cos\phi_1 \sin\omega t = I_{sm} \sin\omega t \qquad (6)$$

where,

$$I_{sm} = I_1 \cos\phi_1 \qquad (7)$$

The total peak current supplied by the source is

$$I_{sp} = I_{sm} + I_{sl} \qquad (8)$$

If the active filter provides the total reactive and harmonic power, then $i_s(t)$ will be in phase with the utility voltage and purely sinusoidal. At this time, the active filter must provide the following compensation current as

$$i_c(t) = i_L(t) - i_s(t) \qquad (9)$$

Design of DC side capacitor:

The DC side capacitor is maintain a DC voltage with small ripple in steady state and energy storage element to supply real power difference between load and source during the transient period. The real/reactive power injection may result in the ripple voltage of DC capacitor. The selection of C_{DC} can be governed by reducing the voltage ripple. The specification of peak to peak voltage ripple and the rated filter current define the capacitor as [2]

$$C_{DC} = \frac{\pi * I_{c1,rated}}{\sqrt{3}\omega V_{dr,p-p(\max)}} \qquad (10)$$

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 active filter.

(4) The PWM converter is assumed to operate in the linear modulation index ($i.e. 0 \le m_a \le 1$).

III. PROPOSED CONTROL SCHEME

The proposed control system consists of reference current control strategy and PWM control method of hysteresis current modulator.

A) Reference current control strategy:

The peak value of the reference current I_{sp} can be estimated by controlling the DC side capacitor voltage. The DC side capacitor voltage effectively controlled by the combination of PI with FLC. The desired reference source currents, after compensation, can be given as

$$i_{sa}^* = I_{sp} \sin \omega t \qquad (11)$$

$$i_{sb}^* = I_{sp} \sin(\omega t - 120^0) \qquad (12)$$

$$i_{sc}^* = I_{sp} \sin(\omega t + 120^0) \qquad (13)$$

Where $I_{sp} = I_{sm} + I_{sl}$ the amplitude of the desired source current and the phase angle is can be obtained from the source voltages. The capacitor voltage is compared with reference value and the error is processed in the PI with fuzzy controller shown in fig 2. The output of the fuzzy controller has been considered as the amplitude of the desired source current. The reference currents are estimated by multiplying this peak value with the unit sine vectors in phase with the source voltages.

Unit sine vector:

The source voltages are converted to the unit current(s) while corresponding phase angles are maintained. The unit current is defined as

$i_a = \sin \omega t,\ i_b = \sin(\omega t - 120^0)$ *and* $i_c = \sin(\omega t + 120^0)$ The amplitude of the sine current is unit or 1 volt and frequency is in phase with the source voltages. This unit current multiplies with peak value of fuzzy logic output for generate the reference current.

PI with Fuzzy controller:

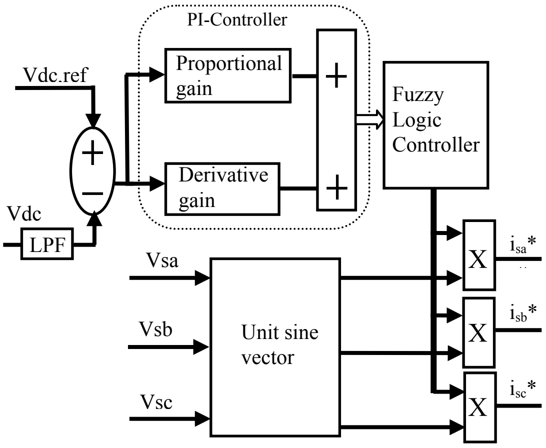


Fig 2 PI with fuzzy logic Controlerl block diagram

Figure 3 shows the block diagram of the proposed PI with fuzzy logic control scheme of an APLC. The DC side capacitor voltage is sensed and filtered using Butterworth low pass filter (LPF) at 50 HZ. This LPF output voltage compared with a reference value. The error $e = V_{dc,ref} - V_{dc}$ at the n^{th} sampling instant is used as input for PI controller. PI controller used to control the PWM-VSI of dc side capacitor voltage. Its transfer function can be represented as

$$H(s) = K_P + K_I / s \qquad (14)$$

where, K_P is the proportional constant [K_P =0.3] that determines the dynamic response of the DC-bus voltage control and K_I is the integration constant [K_I =15] that determines it's settling time. The PI controller output having certain ripple voltage, so as well as need another process to reduce the ripple; the FLC controller connected together with PI controller for rectify the ripple voltage problems.

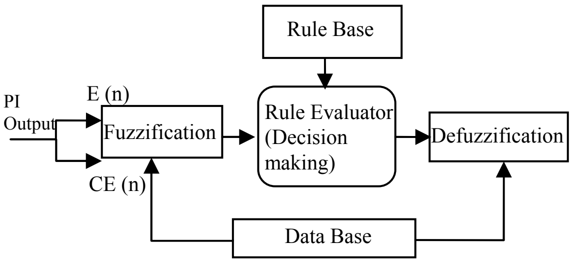


Fig 3 fuzzy logic Control block diagram

Fuzzy logic controller block diagram shown in fig 3, is derived the transition between membership and non membership can be gradual. The PI controller output error is used as inputs for fuzzy processing. The output of the fuzzy controller after a limit is considered as the magnitude of peak reference current I_{sp} .

<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), positive big (PB), negative big (NB). The process of converting a numerical variable (real number) convert to a linguistic variable (fuzzy number) is called fuzzification.

<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 (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 rules used in this paper in table 1.

Table 1 Rule base table

ce(n) e(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

B) Hysteresis Band Current Control:

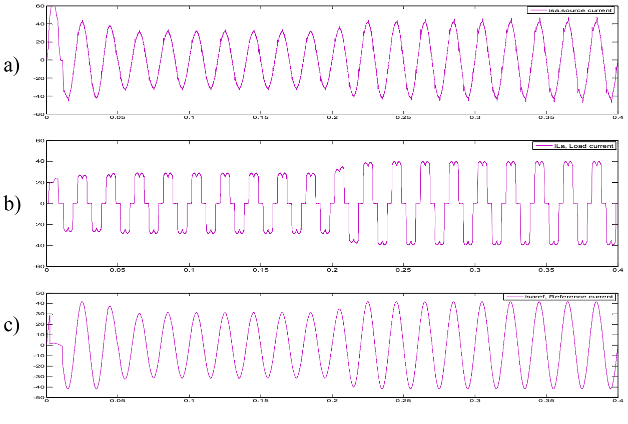
Hysteresis current control is the easiest control method to implement by Brod and Novotny in 1985[5]. A hysteresis current controller is implemented with a closed loop control system. An error signal, $e(t)$, is used to control the switches in an inverter. This error is the difference between the desired current, i_{ref}(t), and the current being injected by the inverter, $i_{actual}(t)$. When the error reaches an upper limit, the transistors are switched to force the current down. When the error reaches a lower limit the current is forced to increase. The range of the error signal, $e_{max} – e_{min}$, directly controls the amount of ripple in the output current from the PWM-voltage source inverter.

IV. SIMULATION RESULT AND ANALYSIS

The SIMULINK toolbox in the MATLAB software in order 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 parameters values are; source voltage (Vs) is 230 Vrms, System frequency (f) is 50 Hz, Source impedance of R_S, L_S is 1 Ω; 0.2 mH respectively, Filter impedance of R_c, L_c is 1 Ω; 2.5 mH, Load impedance of R_L, L_L of diode rectifier RL load in Steady state: 20 Ω; 200 mH and Transient: 10 Ω; 100 mH respectively, DC link capacitance (C_{DC}) is 1600µF, Reference Voltage (V_{DC}) is 400V and Power devices build by IGBT/Diode.

PI with Fuzzy controller

PI with Fuzzy logic controller based APLC system comprises of a three-phase source, a nonlinear load (six pulse diode rectifier RL load) and a PWM voltage source inverter with a dc capacitor input. The simulation time T=0 to T=0.4s with load of diode rectifier with R L load parameter values of 20 ohms and 200 mH respectively. The source current after compensation is presented in fig. 4 (a) that indicates the current becomes sinusoidal. The load current is shown in (b). The actual reference currents for phase (a) are shown in fig. 4(c). This wave is obtained from our proposed controller. The APLC supplies the compensating current that is shown in Fig. 4(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. 4(e), phase (a) voltage and current are in phase.



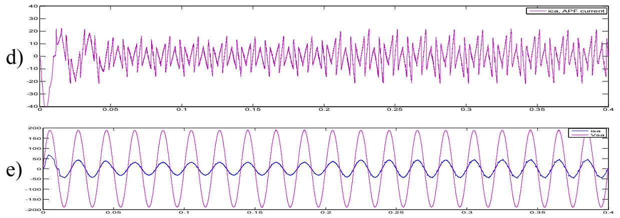


Fig.4 PI with Fuzzy logic controller based simulation results for three-phase active-power-filter under the steady state condition (a) Source current after APF, (b) Load currents, (c)Reference currents by the Fuzzy logic algorithm, (d) Compensation current by APF and (e) source voltage per current for unity power factor

First for simulation time T=0 to T=0.4s with load of rectifier with R L load of 20 ohms and 200 mH respectively and after the R L load of 10 ohms and 100 mH change for transient condition. The transient simulation waveforms are verified similar to steady state waveforms shown in fig 5.

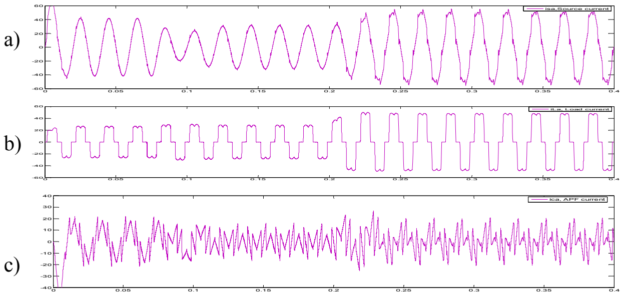


Fig.5 PI with Fuzzy logic controller based simulation results for three-phase active-power-filter under the transient condition (a) Source current after APF, (b) Load currents and (c) Compensation current by APF

The DC side capacitor voltage effectively controlled by the PI or FLC and/or combination of PI with FLC shown in fig 6.

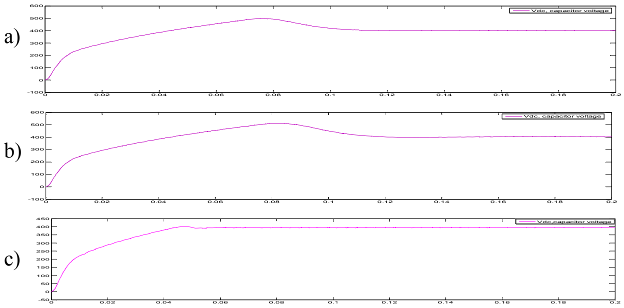


Fig.6 simulation results for three-phase active-power-filter under the steady state condition of DC side capacitor voltage controlled by (a) PI controller (b) FLC controller (c) PI with FLC controller

The summarized PWM- voltage source inverter of capacitance voltage (Vdc) settling time in transient and steady state condition using different controller as shown 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	0.064s
Transient	0.12s	0.118s	0.06s

The active power (P) and reactive power (Q) are calculated by averaging the voltage-current product with a running average window over one cycle of the fundamental frequency, shown in fig 7

$$P = \frac{1}{T}\int_{t-T}^{t} V(\omega t) \times I(\omega t)\,dt \qquad (15)$$

$$Q = \frac{1}{T}\int_{t-T}^{t} v(\omega t) \times i(\omega t - \pi/2)\,dt \qquad (16)$$

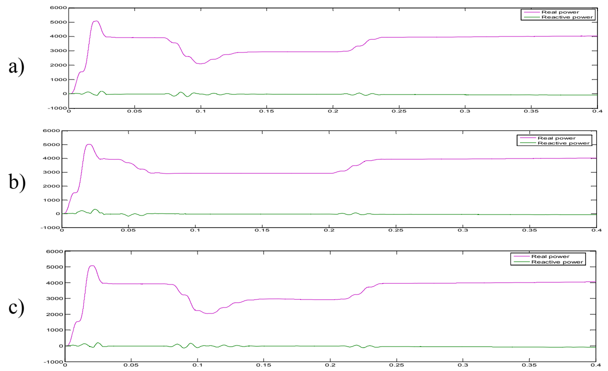


Fig.7 simulation results for three-phase active-power-filter under the steady state condition of real and reactive power analysis for power quality improvements by different controller (a) PI controller (b) FLC controller (c) PI with FLC controller

The PI with fuzzy logic controller based APLC system effectively suppress the reactive power and improve the power factor. The summarized Real (P) and Reactive (Q) power calculation under steady state and transient condition given below, shown 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=0.219 KW	PI	P=4.039 KW Q=0.081 KW
		Fuzzy	P=4.033 KW Q=0.072 KW
		PI with Fuzzy	P=4.057 KW Q=0.075 KW
Transient	P=4.847 KW Q=268 KW	PI	P=4.97 KW Q=0.041 KW
		Fuzzy	P=4.98 KW Q=0.040 KW
		PI with Fuzzy	P=5.17 KW Q=0.036 KW

The Fourier analysis of the source current signal can be calculating the magnitude and the fundamental or order of harmonic component of the signal, that a signal f (t) can be expressed by a Fourier series of the form

$$f(t) = \frac{a_o}{2}\sum_{n=1,2,3..}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t) \qquad (3)$$

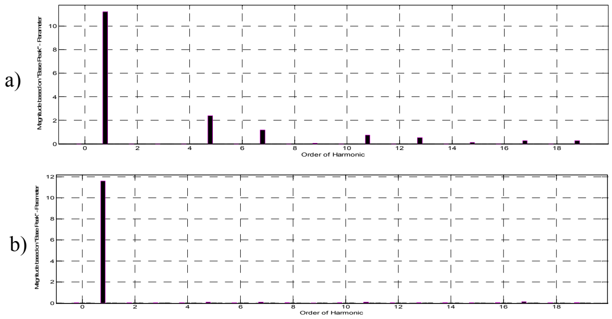


Fig.8 Fuzzy logic with PI-controller based order of harmonics measured with respect to the magnitude under the steady state condition (a) Source current without APF, (b) source currents with APF

The order of harmonics measured with respect to the magnitude or amplitude in volts shown in fig 8.

The total harmonic distortion measured of a periodic distorted signal. The current and voltage of the THD is defined as the root mean square value of the total harmonics of the signal divided by the RMS value of its fundamental signal. The current of the THD is defined as $THD = I_H / I_F$

The analysis of the shunt APLC brings the THD of the source current is less than 5% into 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 with fuzzy logic controller based Shunt APLC performs quite well and it reduces harmonics and reactive power components. Simulation results demonstrate that source current after compensation is sinusoidal and is in phase with source voltage. The compensation process is designed based on calculation of unit sine vector and it also reduces the ripple voltage of the dc capacitor of the PWM-voltage source 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 APLC is in compliance with the IEEE-519 standards harmonics.

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