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Fuzzy Controlled Harmonic Suppressor and Reactive Volt Ampere Compensator for Enhancing Power Quality

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Abstract

This paper presents and compares the performance of two controllers namely Fuzzy Logic and Proportional Integral applied to a voltage source inverter/converter operating as an active power filter. The active power filter is operated to compensate harmonics and reactive power generated by the non-linear load and power factor correction simultaneously. This work is performed in order to make an accurate comparison of fuzzy logic controller and classical control technique such as PI controller. Fuzzy control rule design is based on the general dynamic behavior of the process. A novel control method for a reactive volt–ampere compensator and harmonic suppressor system is proposed. It operates without sensing the reactive volt–ampere demand and nonlinearities present in the load. The compensation process is instantaneous, which is achieved without employing any complicated and involved control logic.

Keywords -– Voltage Source Converter; Active Power Filter; Fuzzy controller; Hysteresis controller; Non linear Load.

1. Introduction

Modern semiconductor switching devices are being utilized more and more in a wide range of applications in distribution networks, particularly in domestic and industrial loads. Examples of such applications widely used are adjustable-speed motor drives, uninterruptible power supplies (UPSs), computers and their peripherals, consumer electronics appliances (TV sets for example), efficient control of heating and lighting, efficient interface for photovoltaic and high voltage dc system for efficient transmission of power, to name a few. Those power electronics devices offer economical and reliable solutions to better manage and control the use of electric energy. However, given the characteristics of most power electronics circuits, those semiconductor devices present nonlinear operational characteristics, which introduce contamination to voltage and current waveforms at the point of common coupling of industrial loads. These devices, aggregated in thousands, have become the main polluters, the main distorters, of the modern power systems [1].

In recent years, the applications of power electronics have grown tremendously. These power electronic system offer highly nonlinear characteristics. An increase in such nonlinearity causes various undesirable features such as: increased harmonics and reactive power components of current from AC mains, low system efficiency and a poor power factor, cause disturbance to other consumers, interference in nearby communication network, unexplained computer network failures, premature motor burnouts, humming in telecommunication lines, transformer overheating, harmonic-induced heating, therefore, thermal trip devices (i.e. circuit breakers and fuses) could activate to remove the loads on that path from the lines. These are only a few of the damages that quality problems may bring into home and industrial installations. What may seem like minor quality problems may bring whole factories to a standstill [1].

In order to overcome the problems of pollution of power i.e. power quality, active power filters have been researched and developed. In recent years, shunt active power filters based on current controlled PWM converters have been widely investigated and recognized as a viable solution [2]. However, most of them are based on sensing harmonics and reactive volt-ampere requirements of the nonlinear load, and require complex control. Duke and Round [3] have proposed a scheme, in which the required compensating current is determined using a simple synthetic sinusoid generation technique by sensing the load current. This scheme is further modified by sensing line currents only [2, 4], which is simple and easy to implement. However, the conventional PI controller was used for the generation of a reference current template. The PI controller requires precise linear mathematical models, which are difficult to obtain and fails to perform satisfactorily under parameter variations, nonlinearity, load disturbance, etc. Soft computing techniques can be used to simplify and automate the controller design. Even though the fuzzy logic has evolved in eighties these techniques were not considered to be feasible for practical implementation until recently but with the availability of powerful single-chip microcontrollers and digital signal processors, this is no longer an issue.

With these developments fuzzy-logic control over the dc bus of the shunt APF was designed to replace the conventional PI controller [5].

Recently, Fuzzy Logic Controllers (FLCs) have generated a good deal of interest in certain applications [6]. The advantages or FLCs over conventional controllers are that they do not need an accurate mathematical model, they can work with imprecise inputs, can handle lion-linearity, and they are more robust than conventional nonlinear controllers [7].

In this paper we present a fuzzy logic controlled shunt active power filter for the harmonics and reactive power compensation of a nonlinear load. The control scheme is based on sensing line currents only; an approach different from convention ones, which are based on sensing harmonics and reactive volt-ampere requirements of the nonlinear load. The DC capacitor voltage is regulated to estimate the reference current template.

The performance of the fuzzy logic controller is compared with a conventional and PI controller under constant load, variable load. The transient, steady state response of the two controllers have been analyzed. The two controllers have been compared under dynamic conditions also. PWM pattern generation is based on carrier less hysteresis based current control to obtain the switching signals. Simulation results are presented.

2. Compensation Principle

The active power filter is controlled to draw/supply the a compensating current i_f from/to the load to cancel out the current harmonics on AC side and reactive power flow from/to the source there by making the source current in phase with source voltage. Figure 1 shows the basic compensation principle of the active power filter.

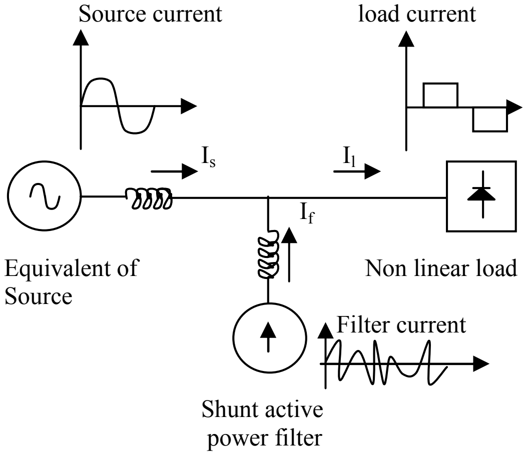

Figure1. Basic Compensation Principle

2.1Significance of DC capacitor

The DC side capacitor serves two main purposes: It maintains a DC voltage with small ripple in steady state and it serves as an energy storage element to supply the real power difference between load and source during the transient period.

When the load condition changes the real power balance between the mains and the load will be disturbed. This real power difference is to be compensated by the DC capacitor. This changes the DC capacitor voltage away from the reference voltage. In order to keep satisfactory operation or the active filter, the peak value of the reference source current must be adjusted to proportionally change the real power drawn from the source. This real power charged/discharged by the capacitor compensates the real power difference between the consumed by the load and that of supplied by the source. If the DC capacitor voltage is recovered and attains the reference voltage, the real power supplied by the source is supposed to be equal to that consumed by the load again [8].

In this fashion the peak value of the reference source current can be obtained by regulating the average voltage of the DC capacitor.

2.2 Estimation of reference source current

Ideal compensation requires the mains current to be sinusoidal and in phase with the source voltage, irrespective of the load current nature. The desired source currents, after compensation, can be given as

$$i_{sa}^{*} = I_{sp} \sin \omega t$$
$$i_{sb}^{*} = I_{sp} \sin(\omega t - 120)$$
$$i_{sc}^{*} = I_{sp} \sin(\omega t + 120) \quad \text{...... (1)}$$

where $I_{sp}\left(= I_1 \cos\phi_1 + I_{sl}\right)$ is the amplitude of the desired source current, while the phase angle can be obtained from the source voltages by multiplying with the unit vectors of respective voltages.

From Figure 1, instantaneous currents can be written as

$$i_s(t) = i_l(t) - i_f(t) \quad \text{....... (2)}$$

where, $i_s(t)$, $i_f(t)$, $i_l(t)$ are instantaneous source, filter and load Currents respectively. Source voltage is given by

$$v_s(t) = V_m \sin wt \quad \text{........ (3)}$$

where, $v_s(t)$, V_m are instantaneous and peak value of source voltages respectively. If a nonlinear load is applied, so the load current can be represented as

$$i_l(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n)$$
$$i_l(t) = I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \quad \text{...... (4)}$$

The instantaneous load power can be given

$$p_l(t) = v_s(t) * i_l(t)$$
$$p_l(t) = p_f(t) + p_r(t) + p_h(t) \quad \text{..... (5)}$$

The real (fundamental) power drawn by the load is given by

$$p_f(t) = v_m I_1 \sin^2 \omega t * \cos\phi_1 = v_s(t) * i_s(t) \quad \ldots\ldots (6)$$

and $p_r(t)$: Fundamental Reactive power,

$p_h(t)$: Harmonic Power

From (6), the source current supplied by the source, after compensation, is

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

where $I_{sm} = I_1 \cos\phi_1$. The utility must supply a small extra amount of current for the capacitor leakage and converter switching losses in addition to the real power of the load. The total peak current supplied by the source, is

$$I_{sp} = I_{sm} + I_{sl} \quad \ldots\ldots (7)$$

Here we are considering the dc link voltage (dc capacitor voltage) for generation of error signal and actual source current is compared with reference source current in hysteresis controller to generate the switching signals. So there is no need of calculations for this small overhead. 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:

$$i_f(t) = i_l(t) - i_s(t)$$

Hence, for accurate and instantaneous compensation of reactive and harmonic power it is necessary to estimate i_s (t), i.e. the fundamental component of the load current the reference current.

Hence, the waveform and phases of the source currents are known (from Eqn. (1)), and only the magnitudes of the source currents need to be determined. This peak value of the reference current has been estimated by regulating the DC side capacitor voltage of the PWM converter [9]. This capacitor voltage is compared with a reference value and the error is processed in a fuzzy controller. The output of the fuzzy controller has been considered as the amplitude of the desired source current, and the reference currents are estimated by multiplying this peak value with the unit sine vectors in phase with the source voltages.

2.3 Estimation of Reference Current Templates

The peak value of the reference current I_{max} is estimated using the fuzzy controller by controlling the DC side capacitor voltage in the closed loop. The output of the fuzzy control algorithm is the change in reference current δI_{max} (n).The peak reference current I_{max} (n) at the n^{th} sampling time is determined by adding the previous reference current I_{max} (n-1) to the calculated change in reference current:

$$i_{max}(n) = I_{max}(n-1) + \delta I_{max}(n) \quad \ldots..(8)$$

In classical control theory this is an integrating effect, which increases the system type and improves the steady state error.

3. Proposed Control scheme

In order to implement the control algorithm of a shunt active power filter in closed loop, the DC side capacitor voltage is sensed and then compared with a reference value. The obtained error

$$e(n) = V_{dc,\,ref}\,(n) - V_{dc,\,act}\,(n) \text{ and}$$

Change of error signal

$$ce(n) = e(n) - e(n-1)$$

at the n^{th} sampling instant are used as inputs for the fuzzy processing. The control scheme is shown in Figure 2.The output of the fuzzy controller after a limit is considered as the amplitude of the reference current I_{max}**.** This current I_{max} takes care of the active power demand of load and the losses in the system The switching signals for the PWM converter are obtained by comparing the actual source currents (i_{sa}, i_{sb}, and i_{sc}) with the reference current templates (i_{sa}^*, i_{sb}^*, and i_{sc}^*) in the hysteresis current controller [10]. Switching signals so obtained, after proper amplification and isolation, are given to switching devices of the PWM converter.

3.1 Basic Fuzzy Algorithm

The internal structure of the fuzzy controller is shown in Figure 3. The error *e* and change of error *ce* are used numerical variables from the real system. 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 Figure 4. The fuzzy controller is characterized as follows:

(i) Seven fuzzy sets for each input and output.
(ii) Fuzzification using continuous universe of discourse.
(iii) Implication using Mamdani's 'min' operator.
(iv) Defuzzification using the 'centroid' method.

3.2 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 input/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'e'&'ce'as inputs.

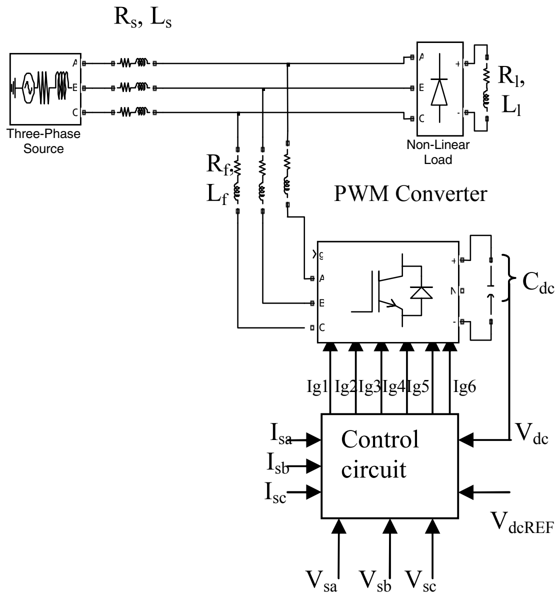

Figure2. Schematic Diagram of Closed Loop Fuzzy Logic Controlled Shunt

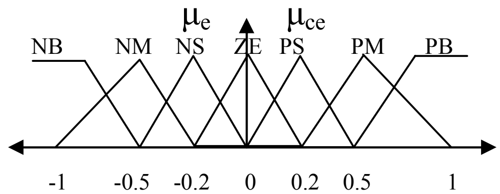

Figure 4(a). Input Normalized Membership Function

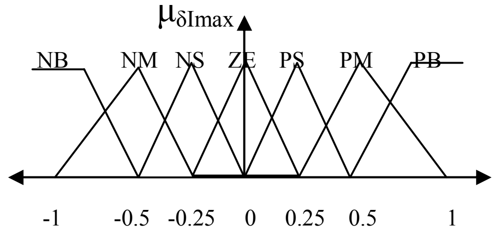

Figure 4(b). Output Normalized Membership Function

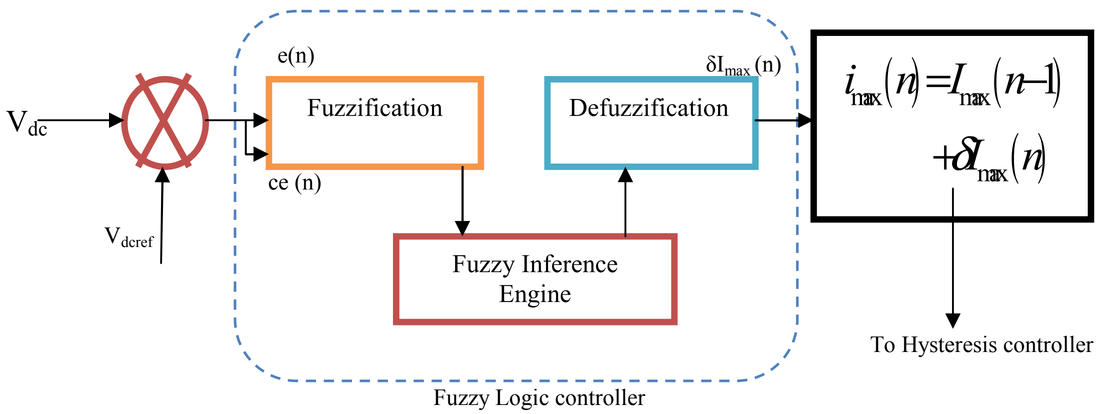

Figure 3. Internal Structure of Fuzzy controller

Table.1 Control rule base

e \ ce	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NB	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

4.PWM Switching Law

The hysteresis current controller decides the switching signals for the devices of the PWM converter. The switchings are obtained *as:*
If $i_{si} > (i_{si}^{*}+hb)$, the Upper switch of the i^{th} leg is ON and lower switch is OFF, If $i_{si} < (i_{si}^{*}+hb)$, theUpper switch of the i^{th} leg is OFF and lower switch is ON, where 'hb' is the hysteresis band around the reference current. The performance of active power filter has been analyzed by solving the above set of differential equations using fourth order Runga – Kutta method.

5. Simulations and Results

System Parameters: Following are the system parameters considered for the study of APF for both PI and Fuzzy controller. $V_s = 100$ V(Peak), f = 50 Hz, $R_s = 0.1\ \Omega$, $L_s = 0.15$ mH, $R_f = 0.1\ \Omega$, $L_f = 0.66$ mH, $R_l = 6.7,15\ \Omega$; $L_l = 20$mH, $C_{DC} = 2000$ uF, Vdcref = 220V. In case of PI the gains chosen are $k_p = 0.2$ and $k_i = 9.32$. Initially the load chosen is of $R_l = 6.7\ \Omega$, $L_l = 20$mH. Responses are shown in Figures 5&6.The load has been changed to $R_l = 15\ \Omega$, L_l=20mH.Responces are shown in Figures 7&8. Again the system was simulated and its performance was analyzed at this new load conditions with both PI and Fuzzy controllers.

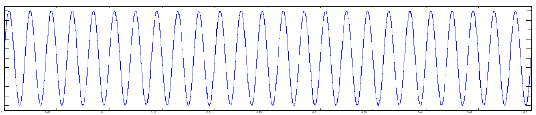
Fig.5 (a) Source voltage

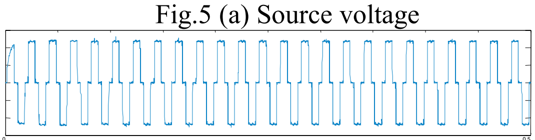
Fig.5 (b) Load current

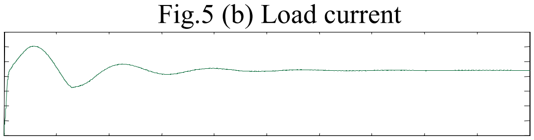
Fig.5 (c) dc capacitor (link) voltage

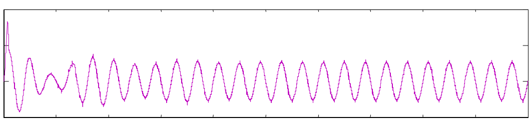
Fig.5 (d) Source current

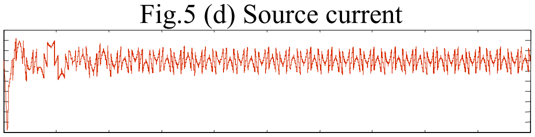
Fig.5 (e) Filter current

Fig.5 Performance of PI Controller for the Load of 6.7 Ohm & 20 mH

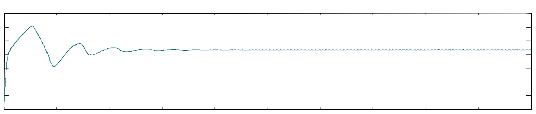
Fig.6 (a) dc capacitor (link) voltage

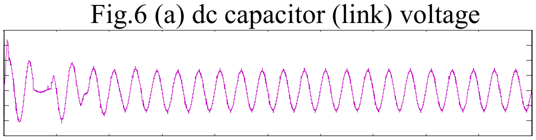
Fig.6 (b) Source current

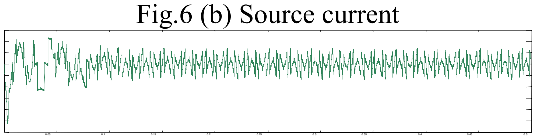
Fig.6 (c) Filter current

Fig.6 Performance of Fuzzy Controller for the Load of 6.7 Ohm & 20 mH

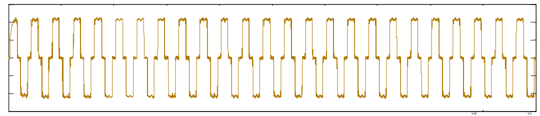
Fig.7 (a) Load current

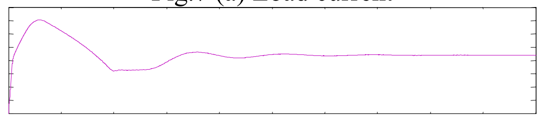
Fig.7 (b) dc capacitor (link) voltage

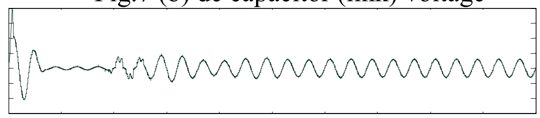
Fig.7 (c) Source current

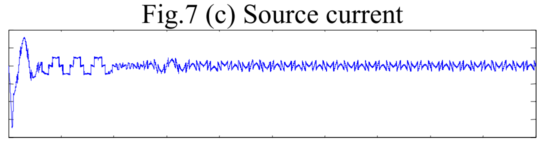
Fig.7 (d) Filter current

Fig.7 Performance of PI Controller for the new Load

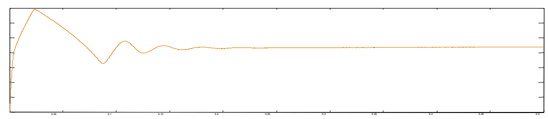
Fig.8 (a) dc capacitor (link) voltage

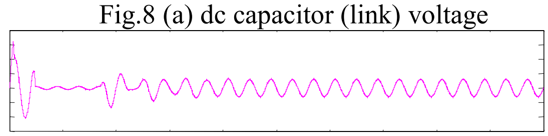
Fig.8 (b) Source current

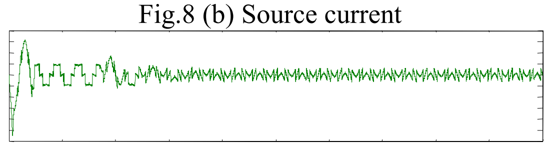
Fig.8 (c) Filter current

Fig.8Performance of Fuzzy Controller for the new Load

System performance is analysed under dynamic conditions also. At initial stage the load on the rectifier side is R_l=10 ohm,L_l=20 mH. After 0.2 second (200 ms) a resistive load of 15 Ohm has been connected suddenly in parallel to this load. In this new operating conditions the compensator performance has been analysed and compared with both PI and Fuzzy controller.The responces are shown in Figures 9 &10.

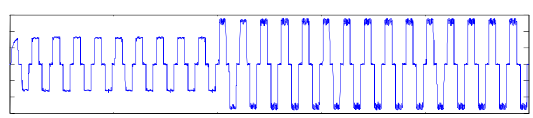
Fig. 9.1(a) Load current

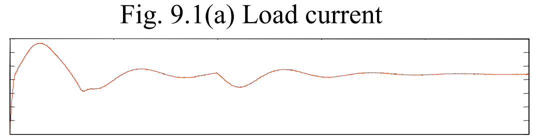
Fig 9.1 (b) dc capacitor (link) voltages

Fig. 9.1 Under Dynamic load change, with PI Controller, response of load current and dc Link voltage.

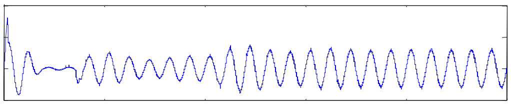

Fig. 9.2 Under Dynamic load change, with PI Controller, response of source current.

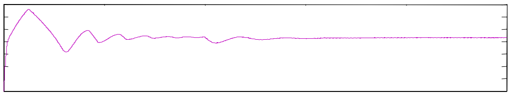

Fig.10 (a) dc capacitor voltage

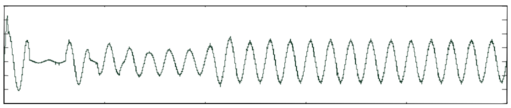

Fig.10 (b) Source current

Fig.10.Under Dynamic load change, with Fuzzy controller.

5.Conclusion

The performance of a fuzzy logic controlled and PI controlled reactive volt ampere compensator and harmonic suppressor has been studied.

Table .2 Comparisons of PI and Fuzzy Controllers

	Settling Time		**% THD**	
	6.7 Ω	15 Ω	6.7 Ω	15 Ω
Load current			28.10	27.72
With PI	≈ 0.26 s	≈ 0.33 s	0.81	1.03
With Fuzzy	≈ 0.18 s	≈ 0.24 s	1.1	0.51

Table .3 Comparison of of PI and Fuzzy controllers under Dynamic load conditions

	PI	**Fuzzy**
Switch on Response (peak overshoot)	≈ 80 A	≈ 65 A
Settling time (after load change)	≈ 0.45 s	≈ 0.3 s
Load Current Overshoot (at load change)	≈ 45 A	≈ 35 A

From the Table.2, it can be concluded that fuzzy controller has a better transient response compared to a conventional PI controller, and the steady state performance of the fuzzy controller is comparable to the PI controller. With reference to Table.3, it can be concluded that the dynamic performance of the fuzzy controller is also better than PI controller. Superior performance of the system with fuzzy controller has been observed, which is able to reduce the harmonics below 5% in all cases studied, the harmonic limit imposed by the IEEE-519 standard.

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