Application of fuzzy-based control approach to three – phase active power via DC link voltage

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Abstract— **One of the most important cases in the power distribution system is to prepare a good quality of the electrical power for consumers, in general. A number of different methods to reach the better quality of the electricity are investigated in academic and industrial environments. In the distribution networks, active filters have the merit to prevent the harmonies, existed in the electrical voltage and corresponding current signals. In a word, the research proposed here is to guarantee the better quality of three-phase active power through fuzzy-based approach that is being used in the designing process of the active filter in controlling procedures. The results of the simulation programs confirm the desirable performance of the proposed control approach, obviously.**

Index Terms— **Distribution system, three – phase active power, fuzzy-based control approach, harmonic.**

I. Introduction

THE power system is a network of electrical components in the production, the transmitting and the utilization of electrical energy [1]. Wreckful loads lead to a number of problems in quality of electric power distribution system, which this is a threat to all consumers (from technically electrical equipment point of view) and even system consumers (in terms of economic as well as network equipment such as transformers and generators damage) [2]. The most important power quality problems that distributed systems are faced no ways are harmonic, unbalanced and reactive loads [3]. In recent years, non-linear loads are increased that cause undesirable phenomena (contains harmonic components) in the power system. In the last two decades with development and manufacture of power electronics component, the use of active filters to eliminate harmonics of current and voltage increased considerably [4]. One of the main goals of the filters in the distribution network, identify the current harmonics that by adjusting this current as a reference for an inverter to compensation of line harmonics currents by injection of suitable voltage [5]. Nowadays in the applied filters in power systems, parallel active filters are more conventional because of its valuable benefits (such as harmonic elimination, high-frequency range, management of reactive power, blocking resonance, small size and accurate adjustment and eliminate random harmonics, etc). The most important problem in applying parallel active power filter in power system is calculating the optimal control strategy and reference voltage for control circuit [6]. In a number of references, many procedures for designing active filter controller both classic and intelligent of different methods have been introduced. One of the shunt active filters with an intelligent controller for electrical network power quality improvement by reducing harmonics is mentioned [7]. The three-phase source current waveform is generated by three-phase converter with hysteresis current control strategy. For reducing distortion the combination of a shunt active filter with three-phase two-arm, bridge power converter is considered [8]. Design and simulation of a controllable DC link voltage hybrid active power filter is discussed for reducing switching losses and noises are also analyzed [9]. For precision and synchrony compensation of harmonics, the structure of the active filter is proposed [10]. Practical active filter control can be implemented with calculation of reference current, control capacitance and pulse width switching control (hysteresis band control) [11].

The smart controller with fuzzy logic implementation is used in control systems design due to the lack of significant advantages, such as independence of dynamic models, dynamism, adaptability and simple structure, easy. The practical applications of fuzzy control systems are power systems distribution and generation, automotive, robotics, home appliances, air-conditioning, temperature control systems, elevators, trains and etc [12].

The main aim of this research is to implement a smart idea derived from fuzzy-based control approach to improve the performance of active filter in the distribution system and achieve more suitable power quality, where it is notable that for verification of theory analysis the simulation programs have been all carried out.

II. The Active Power Filter Structure

Figure 1 shows the shunt connected active power filter (APF) used in this study that based on the control of DC link voltage.

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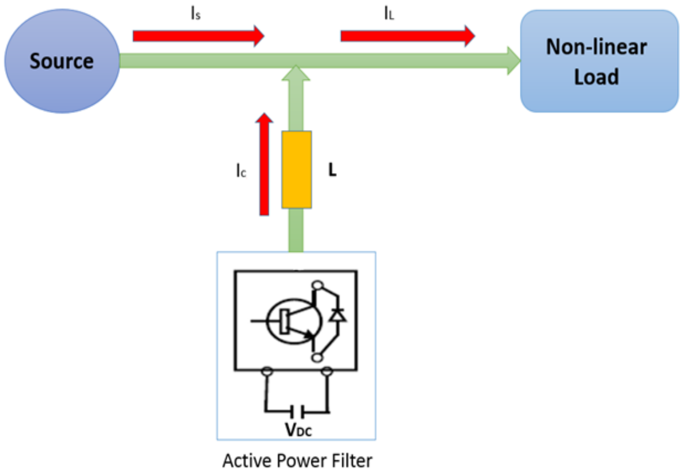


FIG. 1. THE LOCATION OF THE ACTIVE FILTER.

Figure 2 shows the four-wire structure of the shunt active power filter (consist of: IGBT, inverter, controller and dc link).

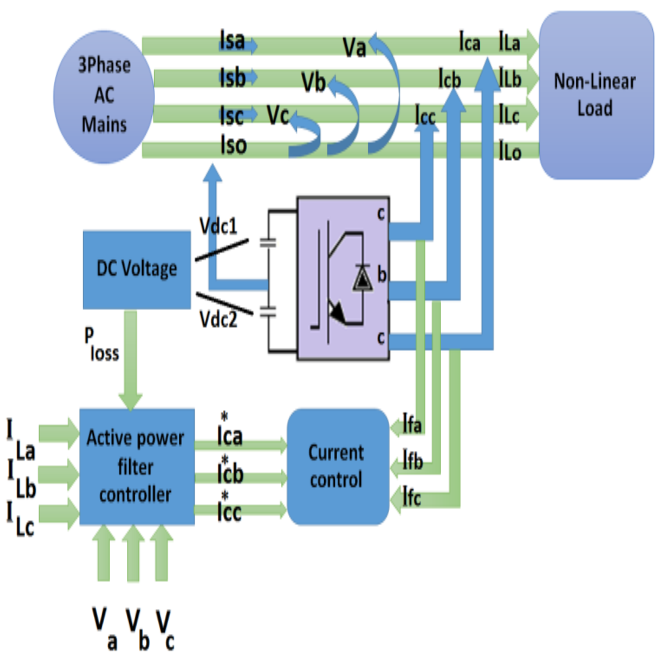


Fig. 2. The three-phase four-wire shunt active filter.

In general, the advantages of the APF are:

- Cancel out harmonics light.
- Block resonance.
- Reactive power management.
- Small size.
- Tuning is easy and accurate.
- It can be used when harmonic components vary, randomly

Details of Figure 2 are explained as follow:

1. Synchronizer a signal processing block based on phase-locked loop techniques that ensure that the deletion waveforms are correctly synchronized to the mains voltage. Definite methods do not require certain synchronization.
2. DC-Bus, an energy store that supplies the swing instantaneous power demand of the inverter. Errors and losses that cause the energy store to engage in long term real power flows must be compensated for by additional action of the inverter controller. Relations for this structure are as follows (equations 1 to 7):

Calculate current and voltage source:

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

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

The nonlinear load current contains the fundamental component and harmonic current components, which is represented as:

$$i_L(t) = \sum_{n=1}^{\infty} i_n \sin(n\omega t + \varphi_n) = I_1 \sin(\omega t + \varphi_1) + (\sum_{n=2}^{\infty} I_n \sin(n\omega t + \varphi_n)) \tag{3}$$

The instantaneous load power can be computed from the source voltage and load current and the calculation is given as:

$$\begin{aligned} P_L(t) &= i_s(t) * v_s(t) \\ &= V_m sin^2\omega t * cos\varphi_1 + V_m I_1 sin\ \ \omega t \\ &* cos\omega t * sin\varphi_1 + V_m sin\omega t \\ &* (\sum_{n=2}^{\infty} I_n \sin(n\omega t + \emptyset_n)) \\ &= p_f(t) + p_r(t) + p_h(t) \end{aligned} \tag{4}$$

This load power contains fundamental (active power), reactive power and harmonic power. Previous calculation has:

$$p_f(t) = V_m I_1 sin^2\omega t * cos\varphi_1 = v_s(t) * i_s(t) \tag{5}$$

If the active power filter provides the total reactive and harmonic power, the source current *is(t)* will be in phase with the utility voltage and sinusoidal. The three-phase source currents after compensation can be expressed as:

$$\begin{aligned} i^*_{sa}(t) &= {p_f(t)}/{v_s(t)} = I_1 cos\varphi_1 sin\ \ \omega t = I_{max} sin\omega t \\ i^*_{sb}(t) &= I_{max}\sin(\omega t - 120^{\circ}) \quad , \quad i^*_{sc}(t) \\ &= I_{max}\sin(\omega t + 120^{\circ}) \end{aligned} \tag{6}$$

A. The P-q model strategy

Balance and unbalanced source voltage is types of disturbance in power system that causes many problems in the aspects of the increased reactive power circulation and the generation of harmonic currents. So, it is quite to employ active power filters to solve these problems due to the balanced and unbalanced input supply since active power filters are designed to provide power factor correction and harmonic compensation. The instantaneous active and reactive power p-q method, p-q method is usually used to design the reactive power and harmonics compensators employing active power filters.

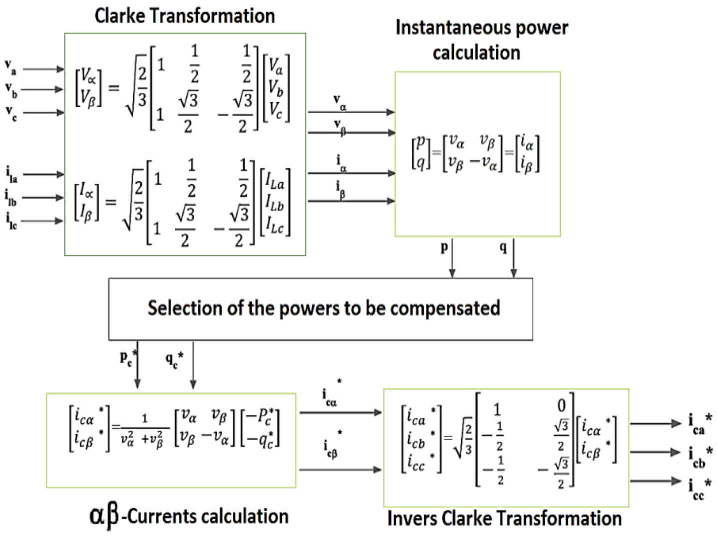


Fig. 3. The block diagram of the *pq* detection method.

The three-phase ac/dc PWM voltage converter connected to the ac mains can also operate as an active power filter. Block diagram of the *pq* detection method shown in Figure 3. In this theory, the system of three-phase devices a, b and c are double-α-β coordinates is transmitted.

III. The DC Link Voltage Regulation via Control Design

For regulating and maintaining the DC link capacitor voltage, the active power flowing into the active filter needs to be controlled [12]. If the active power flowing into the filter can be controlled equal to the losses inside the filter, the DC link voltage can be maintained at the desired value. The quality and performance of the SAF depend mainly on the method implemented to generate the compensating reference currents. This paper presented two methods to get the reference current, which is key issue in the control of the SAF. In order to maintain DC link voltage constant and to generate the compensating reference currents we have been developed two controllers.

1. PI controller.
2. Fuzzy-based control approach.

A. PI controller

Figure 4 shows the PI (proportional-integral) controller that is used in this research. The present PI controller is a special case of the PID controller in which the derivative (D) of the error is not used [6].

1) Active filter equipped via fuzzy controller

Figure 5 is shown fuzzy controller structure that used in this study. Figures 6, 7 and 8 respectively error, integral error and output for designed fuzzy control system with Gaussian membership function (MF) are shows. Considerable that In order to choose the best MF to fuzzy control system, three types of MFs (triangular, trapezoidal, Gaussian) is designed in this study. These rules are typical for control applications in Table I that the antecedents consist of the logical combination of the error and error-delta signals, while the consequent is a control command output.

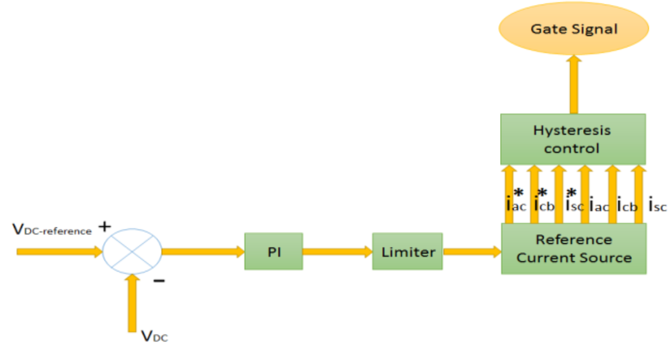


Fig. 4. The PI controller structure.

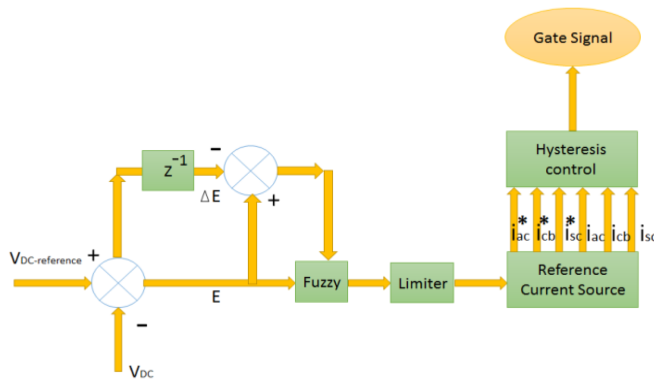


Fig. 5. The fuzzy-based control approach.

TABLE I.
THE FUZZY RULES

e ↓ \ $\int e$ →	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NM	NM	NS	NS	ZE	PS
NS	NM	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PS	PM	PM	PB
PB	ZE	PS	PS	PM	PM	PB	PB

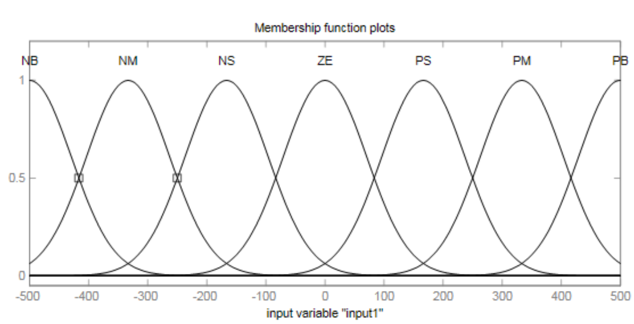


Fig. 6. The Gaussian membership functions (error).

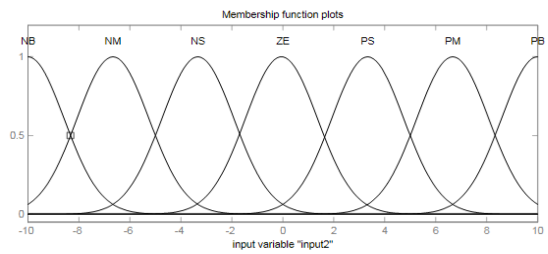


Fig. 7. The Gaussian membership functions (integral error).

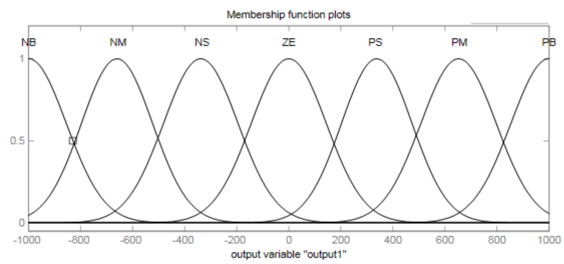


Fig. 8. The Gaussian membership functions (output).

IV. The Simulation Results

The proposed approach is extensively simulated through MATLAB/SIMULINK. This section shows some important results. Note that the comparison of the fuzzy controller is to take care of the unbalance input power, whereas the PI takes care of harmonics of the load and also the harmonics generated due to the hard switching of converter. The passive filters associated with the fuzzy controller and PI mentioned a better response.

A. *Network analysis with filter equipped to PI controller*

Fig. 4 shows the internal structure of the control circuit. The control scheme consists of PI controller, limiter, and three phase sine wave generator for reference current generation and generation of switching signals [8]. The peak value of reference currents are estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through a PI controller, which contributes to zero steady error in tracking the reference current signal. The output of the PI controller is considered as peak value of the supply current (I_{max}), which is composed of two components: (a) fundamental active power component of load current, and (b) loss component of APF; to maintain the average capacitor voltage to a constant value. Peak value of the current (I_{max}) so obtained, is multiplied by the unit sine vectors in phase with the respective source voltages to obtain the reference compensating currents. An optimum PI controller is implemented for shunt active filter structure and simulation results are shown in Figures 9 to 16. Figures 9 and 10 present the details of three-phase source voltage and source current.

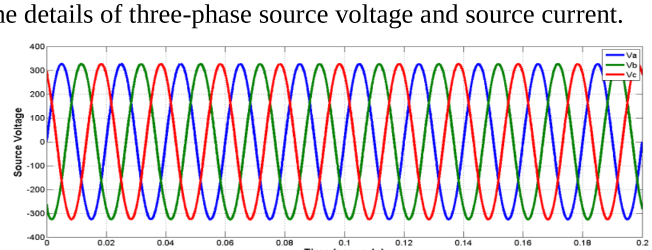


Fig. 9. The source voltage of grid with active filter and PI controller.

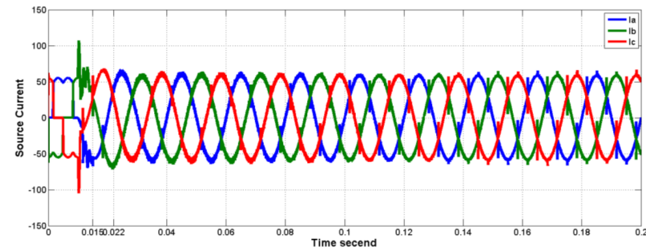


Fig. 10. The source current of grid with active filter and PI controller.

These estimated reference currents and sensed actual currents (I_{sa}, I_{sb}, I_{sc}) are compared at a hysteresis band, which gives the error signal for the modulation technique. This error signal decides the operation of the converter switches. In this current control circuit configuration, the source/supply currents Is_{abc} are made to follow the sinusoidal reference current I_{abc}, within a fixed hysteretic band. The DC link capacitor voltage is kept constant throughout the operating range of the converter. In this scheme, each phase of the converter is controlled independently. To increase the current of a particular phase, the lower switch of the converter associated with that particular phase is turned on while to decrease the current the upper switch of the respective converter phase is turned on. With this one can realize, potential and feasibility of PI controller [13]. As seen in Figure 10, Control system transient response occurred at 0.015 second and source current will have balanced sinusoidal (with acceptable distortion). In Figures 11, 12 and 13, respectively, is indicated non-linear load current, compensation current and DC link voltage. Total harmonic distortion (THD) of PI controller is shown in Figures 14 to 16. According to figures 14 to 16, THD of source current is: Phase 1 about 1.97%, Phase 2 about 1.82% and Phase 3 about 1.89%.

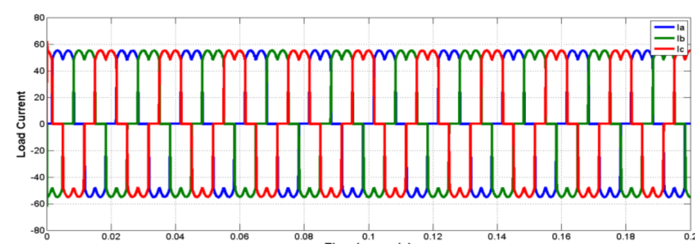


Fig. 11. The load current of grid with active filter and PI controller.

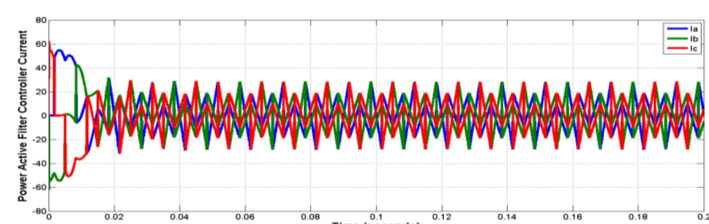


Fig. 12. The compensation current of grid with active filter and PI controller.

Fig. 5 shows the internal structure of the control circuit. The control scheme consists of Fuzzy controller [15], limiter, and three phase sine wave generator for reference current generation and generation of switching signals. The peak value of reference currents is estimated by regulating the

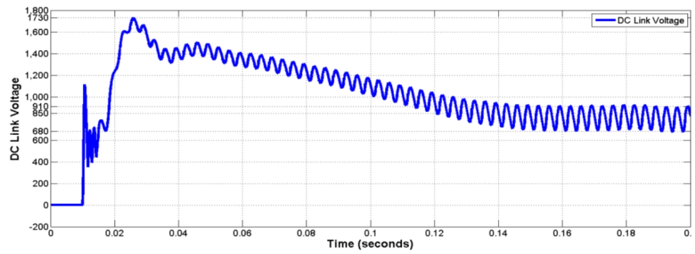


Fig. 13. The DC link voltage

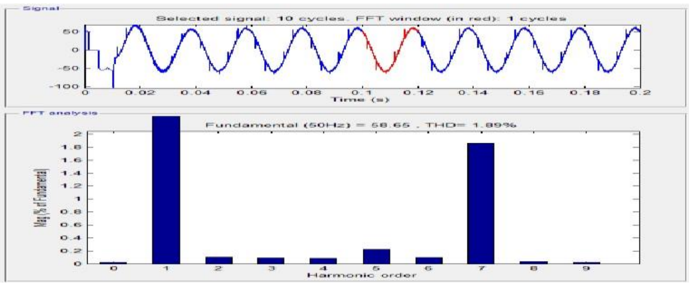


Fig. 14. The THD of source current with PI controller (Phase 1).

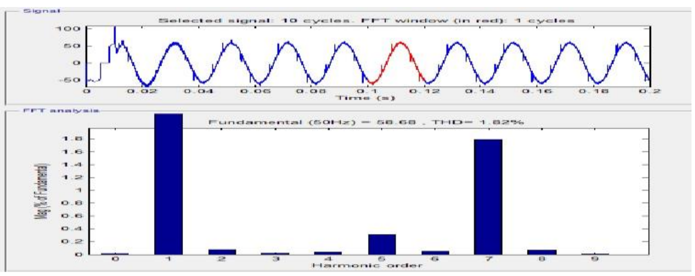


Fig. 15. The THD of source current with PI controller (Phase 2).

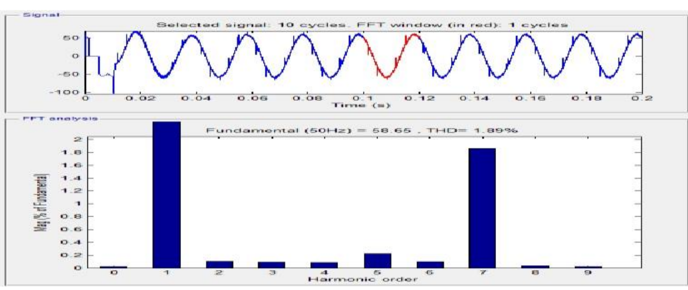


Fig. 16. The THD of source current with PI controller (Phase 3).

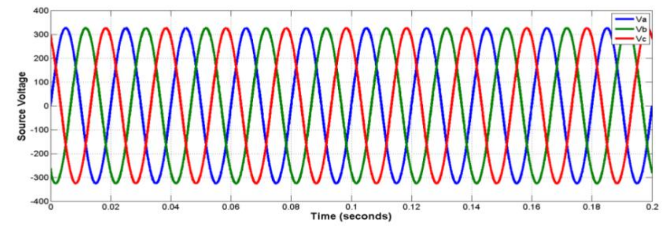
DC link voltage. The actual capacitor voltage is compared with a set reference value.

B. Network analysis with filter equipped to fuzzy controller

The error signal is then processed through a fuzzy controller, which contributes to zero steady error in tracking the reference current signal. 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.

In this section an optimum intelligent controller is implemented for shunt active filter structure and simulation results are shown in Figures 17 to 30. Figure 17 and Figure 18 presents the details of three-phase source voltage and source current. In Figures 18, 19 and 20 respectively is indicated non-linear load current, compensation current and DC link voltage. As seen in Figure 18 Control system transient response occurred at 0.012 second and source current will have balanced sinusoidal (with acceptable distortion). THD of fuzzy controller with Gaussian MF is shown in Figures 28 to 30. According to these figures, THD of source current is: Phase 1 about 1.07%, Phase 2 about 1.10% and Phase 3 about 1.11%.



17: The source voltage.

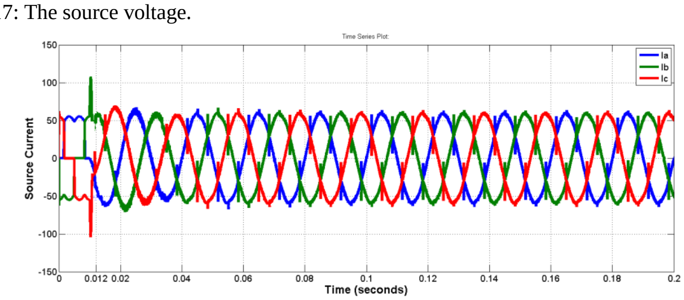


Fig. 18. The source current.

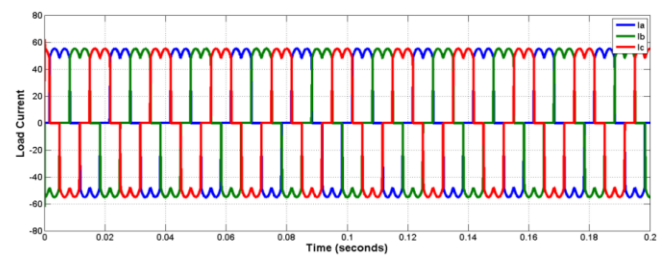


Fig. 19. The load current.

The dc-bus capacitance voltage (Cdc) and its settling time are controlled by fuzzy logic controller (FLC). This controller reduces the ripple to certain level and makes settling time to a low value in both non-linear loads. The Fast Fourier Transform (FFT) is used to measures the order of harmonics with the fundamental frequency at 50 Hz of the source current. The magnitudes of the harmonics are plotted under non-linear load condition and are shown in Fig 22 to 24. From the result, we can observe that fuzzy logic with PLL controller based shunt APF is compensating the harmonics effectively.

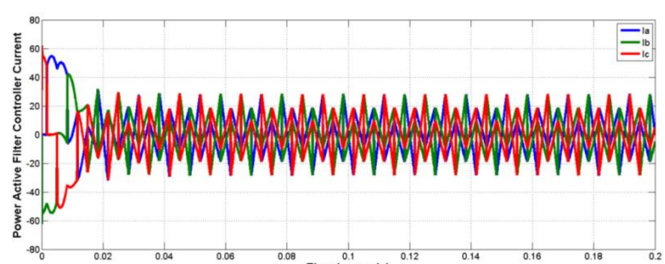


Fig. 20: The compensation current.

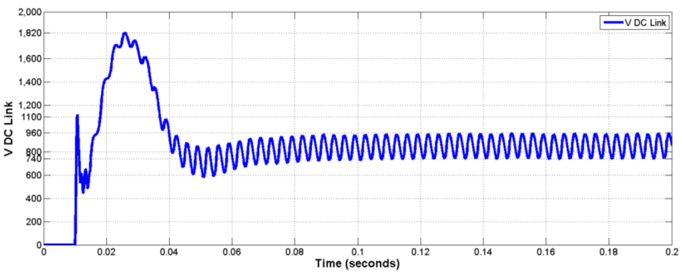


Fig. 21. The DC link voltage.

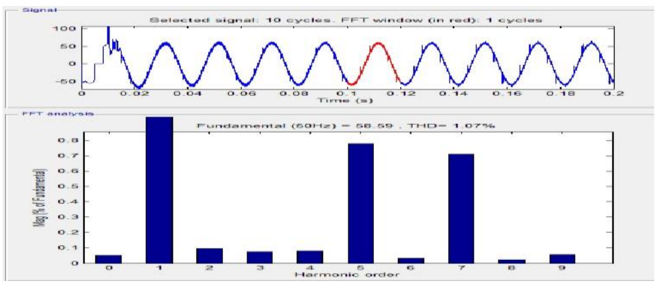


Fig. 22. The THD of source current with Gaussian MF (Phase 1).

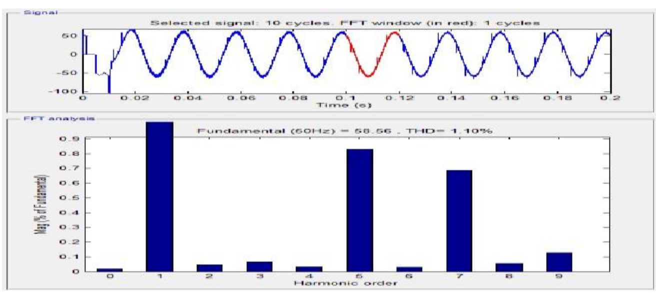


Fig. 23. The THD of source current with Gaussian MF (Phase 2).

C. *Robust of the proposed controller*

To examine the adjustment of the controller proposed in this study, are used an un-balanced three-phase supply. Figure 25 and 26 presents the details of source voltage and load current.

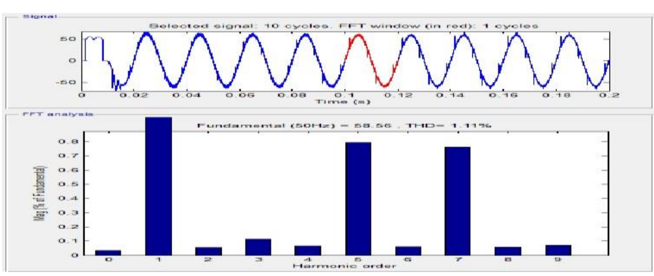


Fig. 24. The THD of source current with Gaussian MF (Phase 1).

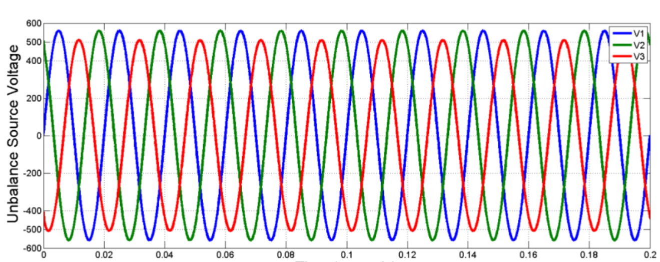


Fig. 25. The source voltage.

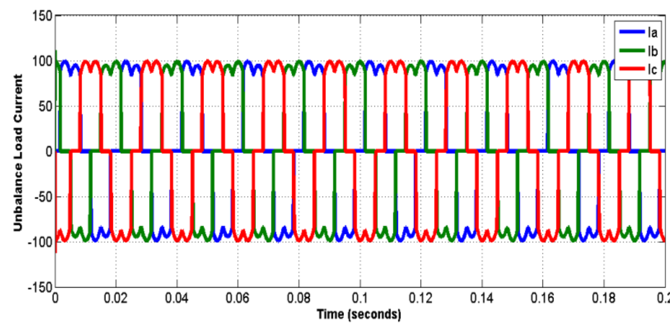


Fig. 26. The load current.

Total harmonic distortion of un-balanced source current with PI controller (THD) is shown in Figures 27 to 29. According to ones, THD of source current is: Phase 1 about 4.36%, Phase 2 about 3.97% and Phase 3 about 4.78%.

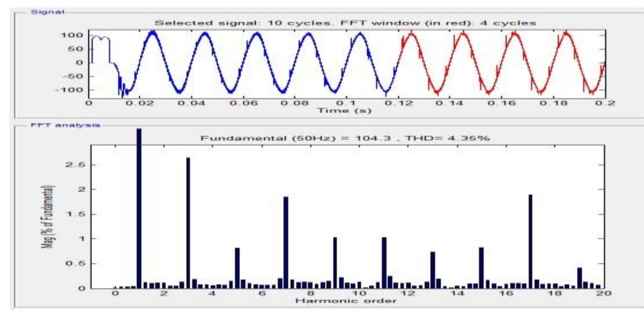


Fig. 27. The THD of un-balanced source current with PI controller (Phase 1).

Total harmonic distortion of un-balanced source current with Gaussian MF controller (THD) is shown in Figures 30 to 32. According to these figures, THD of source current is: Phase 1 about 2.98%, Phase 2 about 2.93% and Phase 3 about 2.89%.

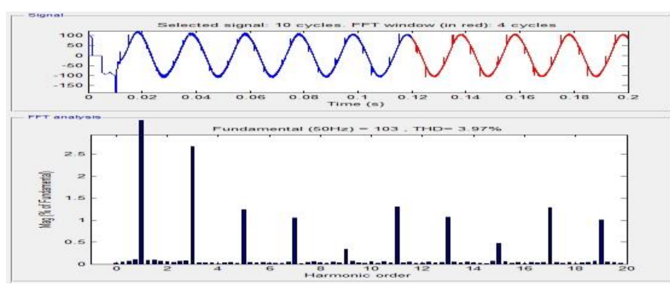


Fig. 28. The THD of un-balanced source current with PI controller (Phase 2).

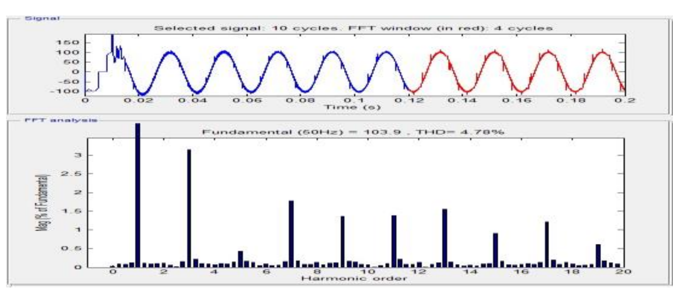


Fig. 29. The THD of un-balanced source current with PI controller (Phase 3).

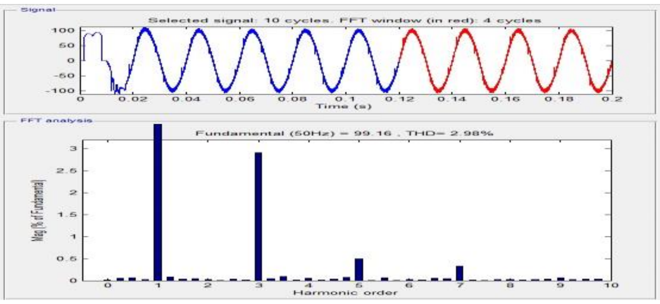


Fig. 30. The THD of un-balanced source current with Gaussian MF (Phase 1).

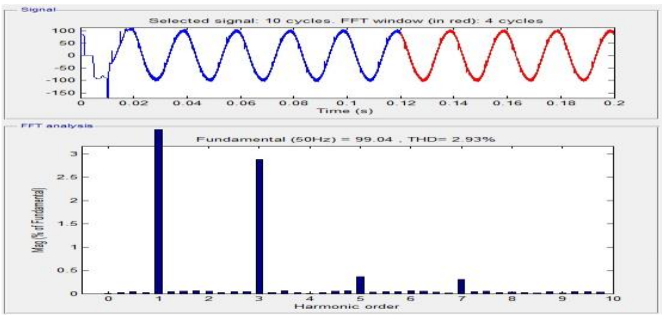


Fig. 31. THD of un-balanced source current with Gaussian MF (Phase 2).

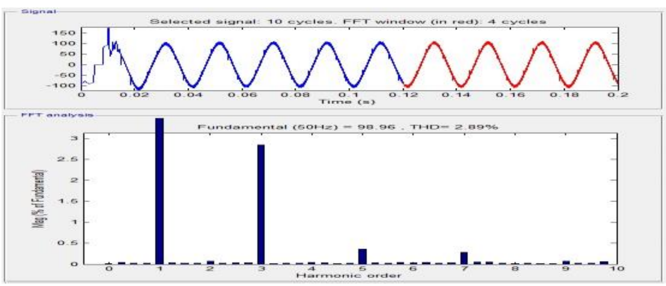


Fig. 32. THD of un-balanced source current with Gaussian MF (Phase 3).

The THD of balanced source current for PI controller, triangular fuzzy, trapezoidal fuzzy and Gaussian fuzzy are all tabulated in Table 2. THD of un-balanced source current for PI controller, triangular fuzzy, trapezoidal fuzzy and Gaussian fuzzy are given in Table 3. Analysis that is related to THD of Tables II and III is mentioned as follow:

1. Control System equipped to PI controller has an appropriate performance,
2. the fuzzy controllers proposed in this study (triangular, trapezoidal and Gaussian) are better performance than PI controller,
3. Active filter equipped to a Gaussian MF controller is lowest THD (best performance) among the other controllers,

TABLE II.
THE THD FOR BALANCED SOURCE

Type of controllers	THD of source current (%)		
	Phase 1	Phase 2	Phase 3
PI	1.97	1.82	1.89
triangular	1.94	1.86	1.86
trapezoidal	1.77	1.82	1.84
Gaussian	1.07	1.10	1.11

TABLE III.
THE THD FOR UNBALANCED SOURCE

Type of controllers	THD of source current (%)		
	Phase 1	Phase 2	Phase 3
PI	4.35	3.97	4.7
Gaussian Fuzzy	2.9	2.93	2.89

V. CONCLUSION

The main objective was to decrease the current harmonics produced by the non-linear loads for the purpose of improving the electrical power quality from the distribution system. The shunt active power filter has shown vitality in eliminating harmonics and reactive power and most of them are based on voltage source inverter. In order to develop source harmonically current are used from p-q control strategy (based on control of DC link voltage), using PI controller and fuzzy controller based on Trapezoidal M.F, Triangular M.F and Gaussian M.F. simulation results showing system control equipped to Gaussian M.F better compensation capabilities in terms of THD compared to other controllers. To explore the robust of the proposed controller in this study, are used an un-balanced three-phase supply.

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