THE PQ0 THEORY WITH MULTI VARIABLE FILTER AND FUZZY LOGIC CONTROL FOR A FOUR LEG SHUNT ACTIVE POWER FILTER COMPENSATED BY THREE DIMENSIONAL SPACE VECTOR MODULATION UNDER UNBALANCED LOADS

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Abstract: *In this paper, a four leg inverter is used as a three phase four wire shunt active power filter, and the fuzzy logic control (FLC) for the reference currents and DC bus voltage controller in the αβo axes for power quality improvements under balanced and unbalanced loads are proposed. In order to, robustness, stabilizing, minimizing the harmonics of source currents, switching losses, reducing the magnitude of neutral current, eliminating the zero-sequence current, and to compensating the reactive power in the four–wire distribution network, and for a good dynamic the pq0 theory with multi variable filter (MVF) in the αβo-axes for generate and extract the reference currents which should be injected by four leg inverter is presented, also to fixed switching frequency and for improved the output voltage forms of this four leg inverter a three dimensional space vector modulation (3D-SVM) is achieved to generate the switching signals.*

Key words: *Four-Leg SAPF, pq0, MVF, Fuzzy logic control (FLC), 3D-SVM, robustness, αβo-axes, zero-sequence current .*

1. Introduction

Harmonics and zero-sequence current are typically caused by using non-linear single-phase loads, i.e. those whose consumed current is not sinusoidal such as single-phase rectifying bridges, speed drives, fluorescent lamps and other single-phase non-linear loads used in both domestic and industrial application. This harmonics increase the losses in all components connected to the system and cause voltage distortion problems [1-3].

The conventional three-leg shunt active power filters are not preferable to compensate the harmonics and zero-sequence current causes by the uses of non-linear single-phase loads connected to a four-wire distribution network [4-7]. To remedy these problems it will be necessary to provide a four-leg shunt active power filter [4],[10-13].

The four leg shunt active power filter connected to the four wire network, has four leg switches reversible current controlled the closing and opening, realized from GTO or IGBT and an anti parallel diode Fig. 1,. The energy storage of the DC bus voltage is done by intermediary of a capacitor C_{dc} subjected to voltage V_{dc}. The output filter, typically first order (R_f, L_f) is used to connect the four leg inverter to the four wire network and to filter the harmonic currents high frequency.

Three principal parts of the four leg shunt active power filter control are the reference currents and DC bus voltage control, reference currents generate, and the switching signals generate. The performances of the four leg shunt active power filter based strongly on the techniques used to generate and controlling the reference current and the strategy used to generate the switching signals into the four leg inverter.

Several techniques for generating switching signals to the four-leg inverter with have been shown in the literature, such as the hysteresis [1], and the PWM [5, 9]. In this study, we use a three dimensional space vector modulation (3D-SVM) [10-14], for generating the switching signals into the four leg inverter. In addition to the nonlinearity and the large parameter variations, many of these techniques no assume ideal conditions and have an enough low response which limit their problems. Fuzzy logic control is theoretically excellent in terms of decoupling the nonlinearity, robustness to parameter variations, and disturbance rejection capabilities [11]. In this paper, this control technique is used and developed.

The pq0 theory for generating the reference signals which should be injected by the SAPF with the low pass filter (LPF) for extracting harmonic or power components, allows obtaining a more or less sufficient elimination of the continue components, because:

- Generally, For proper extraction, the dynamic system is slow, the cutoff frequency is chosen to be bass, between 5 and 35Hz, which causes instability of the active power filter during rapid load change.
- Otherwise, if we choose a higher cutoff frequency, the accuracy of the determination of the alternating component is impaired and may be insufficient.

For these reasons, a new type of extraction filter named multi-variable filter (MVF). Its basic principle is based on the work of [9] and [18]. It is based on the extraction of the fundamental component of the powers, directly according to the αβo-axes.

Currently, researchers are still continuing to improve the forms of the inverter output voltage to obtain the best results, both from the point of view of a better extraction of disturbances (improving the dynamic regime, reduction THD, low switching losses, etc ...) that used a new four-leg inverter control technology for better quality waveforms.

In this paper, the four-leg shunt active filter is controlled by the three-dimensional pulse widths Space Vector modulation (3D-SVM) technique.

This paper presents a comparison study of four control techniques achieving a four-leg shunt active power filter control. Different controllers are used to generating, extracting and controlling the reference currents. These techniques are: PI regulator with pq0 theory based on LPF and MVF, and Fuzzy logic regulator with pq0 theory based on LPF, and MVF.

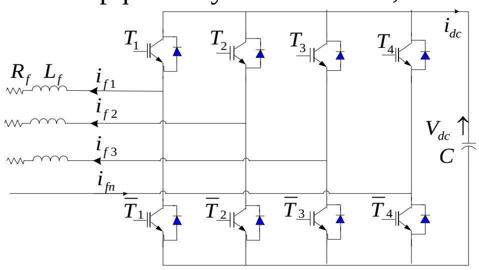


Fig. 1. Schematic of the four leg inverter

2. Mathematical model of the four leg SAPF

The differential equations describing the dynamic model of the four-leg shunt active power filter are defined in αβo-axes, as given in equation (1) [10].

$$\begin{cases} \dfrac{di_{f\alpha}}{dt} = -\dfrac{R_f}{L_f} i_{f\alpha} + \dfrac{1}{L_f} v_{f\alpha} - \dfrac{1}{L_f} v_{l\alpha} \\ \dfrac{di_{f\beta}}{dt} = -\dfrac{R_f}{L_f} i_{f\beta} + \dfrac{1}{L_f} v_{f\beta} - \dfrac{1}{L_f} v_{l\beta} \\ \dfrac{di_{fo}}{dt} = -\dfrac{R_f}{L_f} i_{fo} + \dfrac{1}{L_f} v_{fo} - \dfrac{1}{L_f} v_{lo} \\ \dfrac{dV_{dc}}{dt} = \dfrac{P_{dc}^*}{C\,V_{dc}} \end{cases} \tag{1}$$

The neutral current i_{sn} and zero sequence current are i_o related by the equation below:

$$i_o = \frac{1}{\sqrt{3}}\left(i_{s1} + i_{s2} + i_{s3}\right) = \frac{1}{\sqrt{3}} i_{sn} \tag{2}$$

3. The pq0 theory

The instantaneous real, imaginary and zero-sequence powers pq0 theory has been successfully employed in a wide field of applications, and many contributions have been made in order to generalize it [7], [10]. It has also been applied successfully in controllers of active power filters.

The real power p_l, the imaginary power q_l and the zero-sequence power p_{lo} are expressed by the following matrix:

$$\begin{bmatrix} p_l \\ q_l \\ p_{lo} \end{bmatrix} = \begin{bmatrix} v_{l\alpha} & v_{l\beta} & 0 \\ -v_{l\beta} & v_{l\alpha} & 0 \\ 0 & 0 & v_{lo} \end{bmatrix} \begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \\ i_{lo} \end{bmatrix} \tag{3}$$

Components of instantaneous real, imaginary and zero- sequence powers can be expressed as the sum of a DC component and an AC component:

$$\begin{bmatrix} p_l \\ q_l \\ p_{lo} \end{bmatrix} = \begin{bmatrix} \bar{p}_l + \tilde{p}_l \\ \bar{q}_l + \tilde{q}_l \\ \bar{p}_{lo} + \tilde{p}_{lo} \end{bmatrix} \tag{4}$$

When $\bar{p}_l, \bar{q}_l$ *et* $\bar{p}_{lo}$ are DC components and $\tilde{p}_l, \tilde{q}_l$ *et* $\tilde{p}_{lo}$ are AC components.

Equation (5), we can deduce the corresponding current components:

$$\begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \\ i_{lo} \end{bmatrix} = \frac{1}{v_{lo}(v_{l\alpha}^2 + v_{l\beta}^2)} \begin{bmatrix} v_{lo}v_{l\alpha} & -v_{lo}v_{l\beta} & 0 \\ v_{lo}v_{l\beta} & v_{lo}v_{l\alpha} & 0 \\ 0 & 0 & (v_{l\alpha}^2 + v_{l\beta}^2) \end{bmatrix} \begin{bmatrix} p_l \\ q_l \\ p_{lo} \end{bmatrix} \tag{5}$$

4. Extraction by a multi-variable filter (MVF)

Multi-Variable Filter can be presented by the following transfer function: [9] and [20]

$$H(s) = \frac{V_{xy}(s)}{U_{xy}(s)} = k_e \frac{(s+k) + j\omega}{(s+k)^2 + \omega^2} \tag{6}$$

The schema of this filter is illustrated in Fig. 2.

In the stationary reference, the expression of the basic components is given by:

$$\begin{cases} \bar{X}_\alpha(s) = \dfrac{k}{s}\left[X_\alpha(s) - \bar{X}_\alpha(s)\right] - \dfrac{\omega}{s}\bar{X}_\beta(s) \\ \bar{X}_\beta(s) = \dfrac{k}{s}\left[X_\beta(s) - \bar{X}_\beta(s)\right] + \dfrac{\omega}{s}\bar{X}_\alpha(s) \end{cases} \tag{7}$$

With: $K=50$.

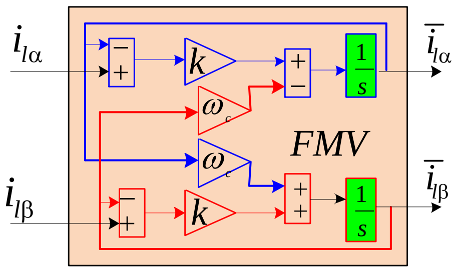


Fig. 2. A Multi-variable Filter

5. Fuzzy logic control

Fuzzy logic control technical is deduced from fuzzy set theory; it was introduced by Zadeh in 1965 [9], these control is theoretically excellent in terms of decoupling the nonlinearity, robustness to parameter variations, disturbance rejection capabilities [11], store the necessary reactive energy, and to reduce the voltage fluctuation under variation or unbalanced loads [11], [20].

The block diagram of a fuzzy controller (FLC) is shown in Fig. 3. [14-19]

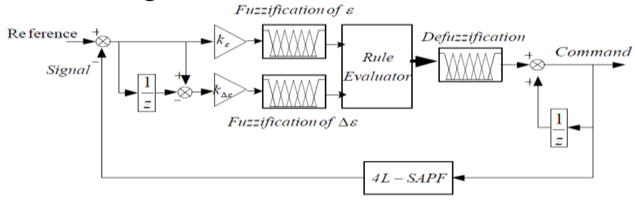


Fig. 3. Basic configuration of fuzzy logic controller

To apply the fuzzy logic control on the four leg shunt active filter in the αβo-axes, the system (1) should be divided into two subsystems as follows:

A. Control currents

The reference voltages $v_{f\alpha\beta o}$ at the input of 3D-SVM block generates by the fuzzy logic controllers (FLC) are used to control the reference currents $i_{f\alpha\beta o}$ will be determined depending on the error between the reference currents and currents injected by the four leg inverter. Each of these fuzzy logic controllers has two inputs, the error of the current ($\varepsilon i_{f\alpha\beta o}$), the derivative of the error ($\Delta\varepsilon i_{f\alpha\beta o}$) and a single output $v_{f\alpha\beta o}$. The membership functions of the input and output variables are shown in Fig. 4 [11]. The fuzzy rule base with 25 rules is given in Table 1.

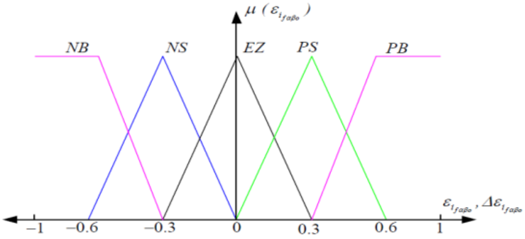


Fig. 4. Membership functions for the input and output variables of the reference currents controller

Table 1.
Fuzzy control rule table of the reference currents controller

		Δε(i_fαβo)				
		NB	***NS***	***EZ***	***PS***	***PB***
ε(i_fαβo)	***NB***	*NB*	*NB*	*NB*	*NS*	*EZ*
	NS	*NB*	*NB*	*NS*	*EZ*	*PS*
	EZ	*NB*	*NS*	*EZ*	*PS*	*PB*
	PS	*NS*	*EZ*	*PS*	*PB*	*PB*
	PB	*EZ*	*PS*	*PB*	*PB*	*PB*

B. DC-bus voltage control

The direct power p_{dc} at the output of fuzzy logic controller (FLC), will be determined according to the error between the reference voltage and the capacitor voltage. This fuzzy controller has two inputs, the error (εV_{dc}), the derivative of this error ($\Delta\varepsilon V_{dc}$) and a single output p_{dc}. The membership functions of the input and output variables are shown in fig. 5. The fuzzy rule base with 49 rules is given in Table 2.

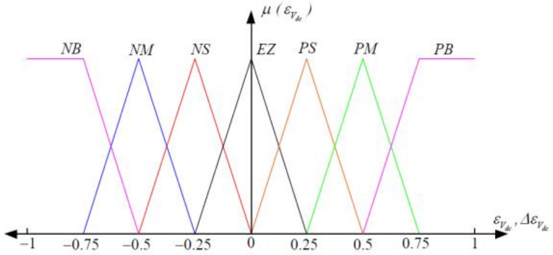


Fig. 5. Membership functions for the input and output variables of the DC-bus voltage control

Table 2.
Fuzzy control rule table of the dc-bus voltage control

		Δε(V_dc)						
		NB	***NM***	***NS***	***EZ***	***PS***	***PM***	***PB***
ε(V_d)	***NB***	*NB*	*NB*	*NB*	*NB*	*NM*	*NS*	*EZ*
	NM	*NB*	*NB*	*NB*	*NM*	*NS*	*EZ*	*PS*
	NS	*NB*	*NB*	*NM*	*NS*	*EZ*	*PS*	*PM*
	EZ	*NB*	*NM*	*NS*	*EZ*	*PS*	*PM*	*PB*
	PS	*NM*	*NS*	*EZ*	*PS*	*PM*	*PB*	*PB*
	PM	*NS*	*EZ*	*PS*	*PM*	*PB*	*PB*	*PB*
	PB	*EZ*	*PS*	*PM*	*PB*	*PB*	*PB*	*PB*

6. Three dimensional space vector modulation (3D-SVM)

This strategy not only inherits the fixation of the switching frequency of the four leg inverter switches, but also improves the form of the output voltage and provides a good dynamic response in the four leg inverter. In 3D-SVM in the four leg inverter, there are 2^4=16 possible switching vectors: fourteen active vectors and two null vectors. The Vector diagram of the four leg inverter is illustrated in Fig. 6. [4]:

Six prisms in the 3D space can be identified and numbered as Prisms 1 through 6. Within the selected prism, there are six non-zero switching state vectors and two zero switching state vectors. Fig. 6 shows the physical positions of the switching state vectors in αβo-axes [10-13].

The working principle of this method is mainly based on, prisms and tetrahedrons identification, duty cycle calculation, and the pulses generation. This method and all the steps are presented and described in detail in various of our previous works [10 -12].

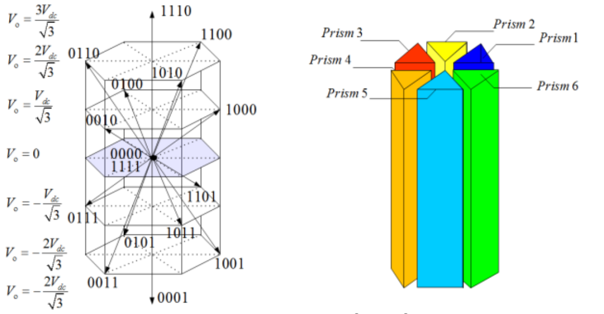


Fig. 6. The Vector diagram of the four leg inverter, switching vectors and the selection of the prisms

7. Simulation model of a four-wire four-leg SAPF

The performance of the proposed control strategy is evaluated through Sim Power Systems and S-Function of MATLAB Fig. 7. The non-linear load consists of single-phase rectifier and Series RL Branch. The components and parameters are listed in Table 3.

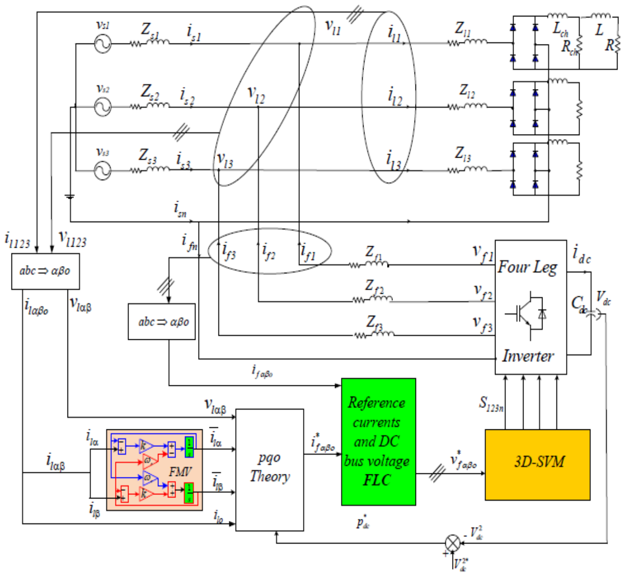


Fig.7. Schematic diagram of three phase four wire four leg shunt active power filter.

Table 3
System parameters for simulation and loads specifications

Parameter	**Value**
Capacitance of the capacitor C_{dc}	5 mF
Coupling impedance R_f ,L_f	0.1 mΩ, 0.1 mH
The source voltage and frequency	220 V, 50Hz
Source impedance R_s ,L_s	1 mΩ, 1 mH
Line impedance R_l ,L_l	1 mΩ, 1 mH
Loads impedance R_{ch} ,L_{ch}	5Ω, 10 mH
Unbalanced Loads R ,L	5Ω, 10 mH

A. *Before filtering*

Fig. 8 shows the current waveform of the loads. It is a highly non-sinusoidal current and deformed and there is not in sync with the corresponding voltages (power factor is $P_f = 0$), the form of the neutral current with a maximum value of 22A in the balanced case and 70A in the unbalanced case.

Figs. 9 (a and b) shows the first phase source current's THD. Before unbalanced loads (t<0.4s), the total harmonic distortion (THD) is 13.92%, when after (t>0.4s) it's 10.51%.

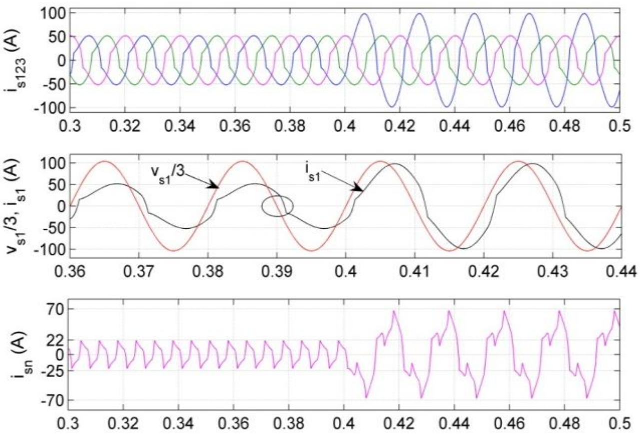
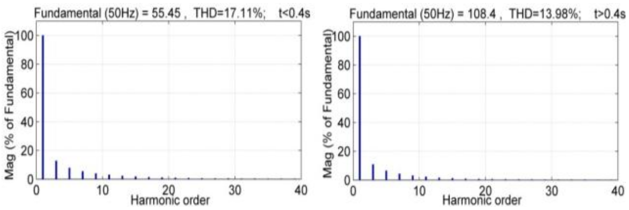


Fig. 8. Simulation results before filtering



(a) (b)

Fig. 9. Magnitude Spectrum of Source Currents before filtering: (a) Before unbalanced loads, (b) After unbalanced loads

B. *After filtering*

To validate the proposed strategies in this paper, the results of numerical simulation are presented in this section. These results were obtained by applying the three phase four wire four-leg SAPF with the Three Dimensional Space Vector Modulation strategy, with the conditions considered for simulation specifications are given in Table 5.

Table 5
The considered conditions for simulation

PI	Fuzzy logic control
f_s =14 kHz	f_s =14 kHz
V_{dcref} =800 V	V_{dcref} =800 V
f_{c}= 10 kHz	$Ke(i_{f\alpha}) = k\,e(i_{f\beta})= 0.001$, $Ke(i_{fo})= 0.012$ $K\Delta e(i_{f\alpha}) = k\Delta e(i_{f\beta})= 5.21*10^{-3}$, $K\Delta e(i_{fo})= 1.12*10^{-3}$
f_{ds} =4Hz	$Ke(Vdc)= 10^{-2}$, $K\Delta e(Vdc)= 2.48*10^{-3}$

The simulation results of the system after compensation with the two reference currents and DC bus voltage control techniques before and after unbalanced loads are given in Figs. 10-13.

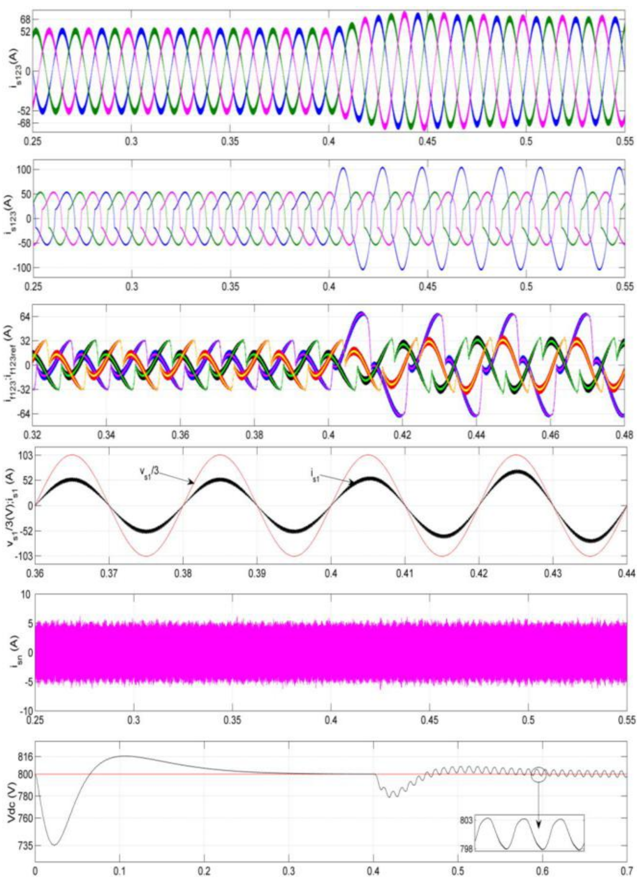
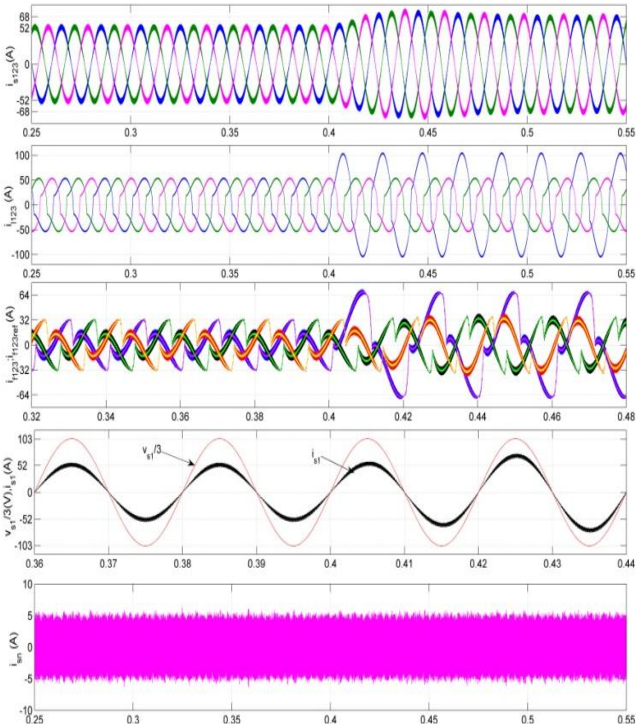


Fig. 10. Performance of the four leg SAPF before and after unbalanced loads, using PI control with LPF



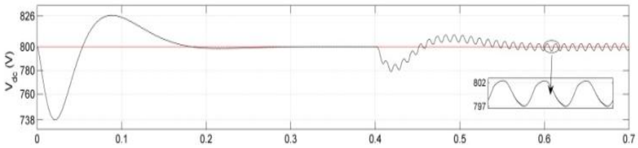


Fig. 11. Performance of the four leg SAPF before and after unbalanced loads, using PI control with MVF

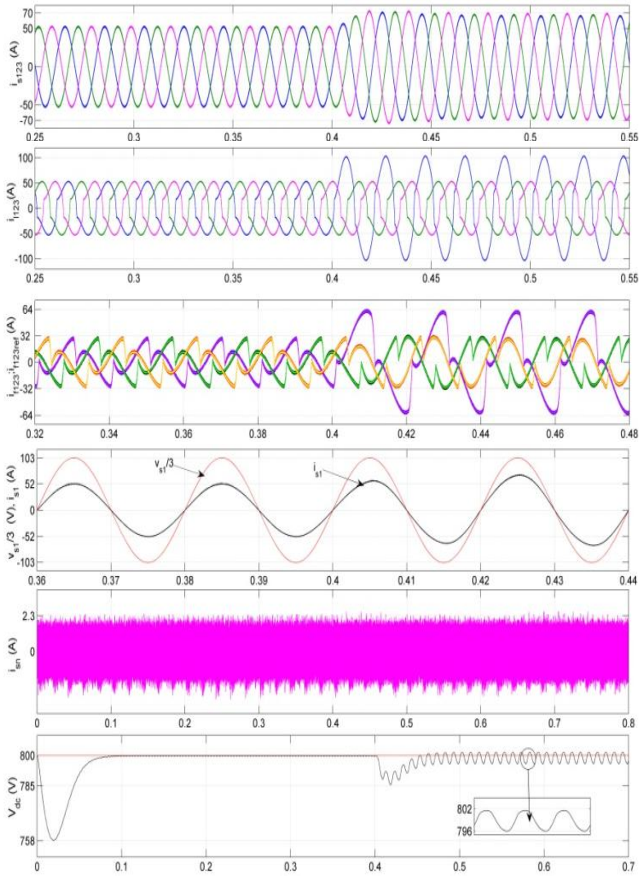
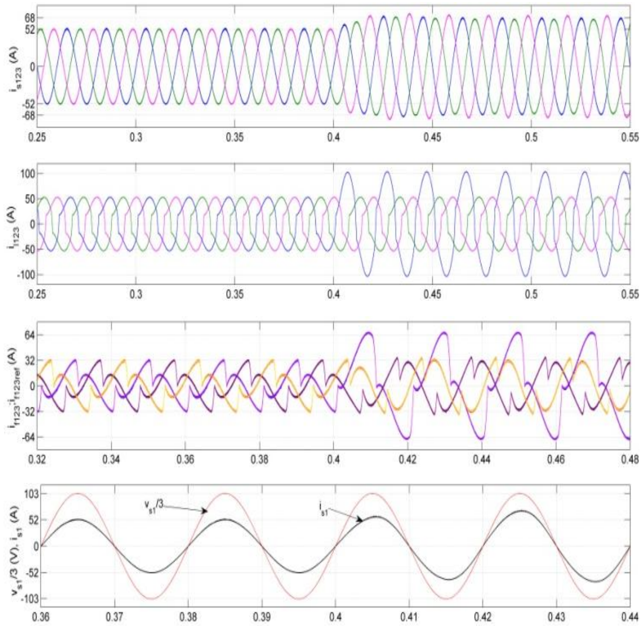


Fig. 12. Performance of the four leg SAPF before and after unbalanced loads, using Fuzzy logic control with LPF



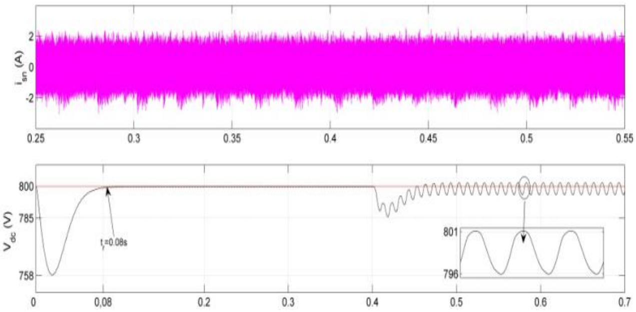
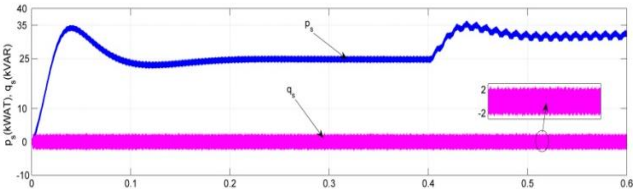
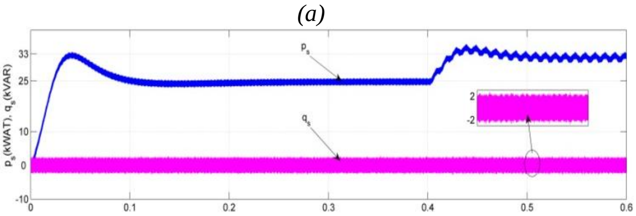


Fig. 13. Performance of the four leg SAPF before and after unbalanced loads, using Fuzzy logic control with MVF



(a)



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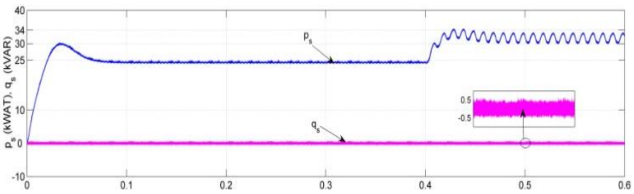

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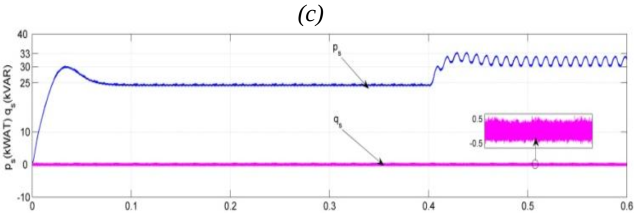
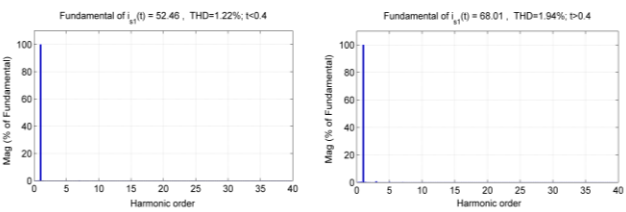
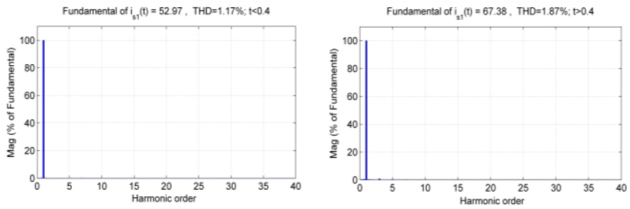


(d)

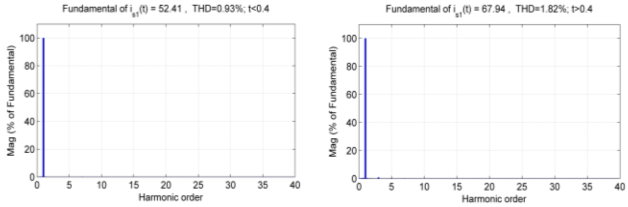
Fig. 14. The real and imaginary powers in the source before and after unbalanced loads: (a) Using PI control with LPF, (b) Using PI control with MVF, (c) Using Fuzzy logic control with LPF, (d) Using Fuzzy logic control with MVF



(a)



(b)



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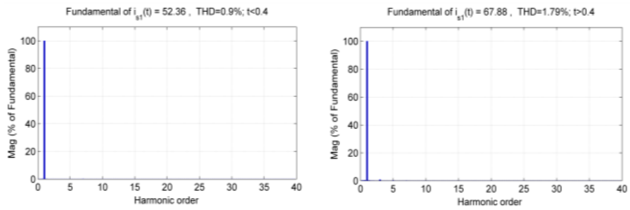

(d)

Fig. 15. THDs of Source Currents before and after unbalanced loads: (a) Using PI control with LPF, (b) Using PI control with MVF, (c) Using Fuzzy logic control with LPF, (d) Using Fuzzy logic control with MVF

Figs. 10–13 illustrate the four feg shunt active power filter performance under different loads conditions and the two controllers with the two types of extraction filter (LPF and MVF), the source currents waveform are sinusoidal and the harmonic reduces with fuzzy logic controller with the two types of extraction filter, the amplitude of the neutral wire current is in the range of ±5 A with LPF and MVF, for the PI control and the range of ±2.3A with LPF and ±2A with MVF for the fuzzy logic controller.

For the two controls with the two types of extraction filter, the real power in the source is constant with an increase after unbalanced loads, the imaginary power is almost zero Figs. 14 (a, b, c, and d), which means also that the source has a power factor almost of unity before and after the unbalanced loads, as well as smaller undulations than in the control by fuzzy logic controller with MVF and the range of ±0.2kVar.

Figs. 15 (a, b, c, and d) illustrates the harmonic spectrum of the first phase source current for the two theories, before unbalanced loads (t<0.4s), total harmonic distortion (THD) is 1.22% with LPF and 1.17% with MVF, for the PI control and 0.93% with LPF and 0.9% with MVF for the fuzzy logic control, when after unbalanced loads (t<0.4s) its 1.94% with LPF and 1.87% with MVF for the PI control, and 1.82% with LPF and 1.79% with MVF for the fuzzy logic control.

The THDs of the source current with the two controllers (PI and FLC) with the two types of extraction filter (LPF and MVF) are well below; the limit imposed by the IEEE-519 or CEI 61000 standards.

8. Conclusion

Instantaneous real, imaginary and zero-sequence powers pq0 theory with the two types of extraction filter (LPF and MVF) in the αβo axes to generate and extract the reference powers and currents which should be injected by the four-leg inverter strategy using PI and FLC for reference currents and DC bus voltage controller are developed to power quality improvements of four leg shunt active power filter by eliminating harmonics of source currents, reducing the magnitude of neutral current, eliminating the zero-sequence current, compensating the reactive power in the four–wire distribution network requirement of the nonlinear single phase loads, eliminating the overshoot of DC bus voltage. The control design using three dimensional space vector modulation for the switching signals generation, reduced switching losses, and to fixed switching frequency have been achieved. The simulation results are validated with Matlab simulink.

The simulation results shows the performance of four feg shunt active power filter based on pq0 theory with MVF using FLC showing better compensation capabilities in terms of source currents THDs, amplitude of neutral current, compared to pq0 theory with LPF using PI and FLC and also pq0 theory with MVF using PI.

The pq0 theory with multi-variable filter (MVF) in the αβo-axes giving a good dynamic for generate and extract the reference currents which should be injected by four leg inverter.

Table 6 gives the THDs, amplitude of the neutral current, and overshoot of the DC voltage comparison of PI and fuzzy logic control the two types of extraction filter (LPF and MVF) before and after unbalanced loads.

Table 6
Comparison of the different techniques

	PI				Fuzzy logic			
	Balanced Loads		Unbalanced Loads		Balanced Loads		Unbalanced Loads	
	LPF	MVF	LPF	MVF	LPF	MVF	LPF	MVF
Source current THD	1.22%	1.17%	1.94 %	1.87%	0.93%	0.9%	1.82 %	1.79%
The amplitude of the i_{sn}	±5A		±5A		±2.3A	±2A	±2.3A	±2A
Overshoot for DC bus voltage	16V	26V	10V	12V	Zero			
Undulations in the imaginary power	±2 kVar				±0.5 kVar			

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