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Comparative Study of Three Phase Four Wire Shunt Active Power Filter Topologies based Fuzzy Logic DC Bus Voltage Control

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Abstract

In this paper, a comparative study based fuzzy logic DC bus voltage control for three phase four wire shunt active power filter for two different inverter topologies, three-leg split-capacitor topology (TLSC) and four-leg inverter (FLFB) are proposed. Identification of reference currents will be developed by classical extraction filters based on pq theory in the first section of the paper. DC-bus voltage control in three-phase four-wire shunt active filter is treated by a fuzzy logic control. A comparison of the proposed method against the conventional proportional integral is illustrated with two different inverter topologies through simulation results and a clear advantage of the fuzzy logic control can be observed. Moreover, the switching pattern of the inverter is generated by a modulated hysteresis current controller. All simulations have been realized in the same conditions so results can be compared with each other. The effectiveness of the proposed method is verified by MATLAB software.

Keywords: *three-leg split-capacitor topology, four-leg inverter, reference current extraction, fuzzy logic controller, modulated hysteresis controller*

1. Introduction

Power quality problems have been drawing more and more attentions these years, especially with the development of modern electronics industry and the continuous proliferation of nonlinear type of electric load. To solve these problems, passive power filters were used at the beginning, and the active power filter APF is now widely researched and used [1]. Passive filters have the limitations of fixed compensation, large size, and that they can create new system resonance [2]. That is why the solution of active power filter has been widely developed this last decade. In severe cases, the neutral currents are potentially damaging to both the neutral conductor and the transformer to which it is connected. Three phase four wire active power filters have been proposed by researchers as an effective solution to these problems [3]. A comparative study of three phase four wire shunt active power filter for two different inverter topologies, three-leg split-capacitor topology (TLSC) and four-leg inverter (FLFB) is proposed in the first part of this paper. The control strategy for a shunt active power filter generates the reference current, that must be provided by the power filter to compensate reactive power and harmonic currents generated by the load. Most APFs have been designed on the basis of instantaneous reactive power theory to calculate the desired compensation current. This theory was first proposed by Akagi and co-workers in 1984, and has since been the subject of various interpretations and improvements [4]. It is detailed in the second part of this paper. The DC-link voltage of inverter must be kept constant in order that APF can compensate harmonics and reactive power effectively.

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Generally, conventional PI controller is applied to control DC-link voltage by adding an active component to the source current reference. The PI controller used requires precise linear mathematical models, which are difficult to obtain, and fails to perform satisfactorily under parameter variations, nonlinearity, load disturbance, etc. It will cause DC voltage overshoot and inrush source current which will lead to protection or even equipment damage when APF is plunged into the system. The voltage overshoot and inrush current were been the constraints which restrict the development of active power filter [5]. Fuzzy Logic Controller (FLC) is proposed in the third part of this paper to solve this problem. The advantages of FLC's over the conventional controllers are: It does not need accurate mathematical model; it can handle nonlinearity and is more robust than conventional controllers. The fourth part of this paper deals with the generation of the switching pattern of the inverter by using a modulated hysteresis current controller.

2. Active Power System Configure

Topology of three-phase four-wire shunt active power filter mainly contains three bridge PWM converters and four bridge PWM converter. The neutral line of third-bridge PWM converter is connected to the split-capacitor inverter while the four bridge PWM converters compensate the neutral current with a bridge. Three-bridge PWM converter needs few electronic devices, but has to control two DC capacitor voltage balances [6]. This paper focuses on a comparison between a split-capacitor three-phase three bridge PWM inverter (TLSC System structure shown in figure1) and four bridge PWM converters (FLFB shown in Figure 2).

2.1. Three Leg Topology

The main circuit of the shunt APF shown in Figure 1 is implemented using the three-leg split-capacitor topology (TLSC). It uses three independent controllers acting on a half bridge pulse width modulation (PWM) VSI converter. A common capacitor is coupled to a dc-bus with the midpoint connected to the neutral wire, while the ac side is connected to the power supply system [7].

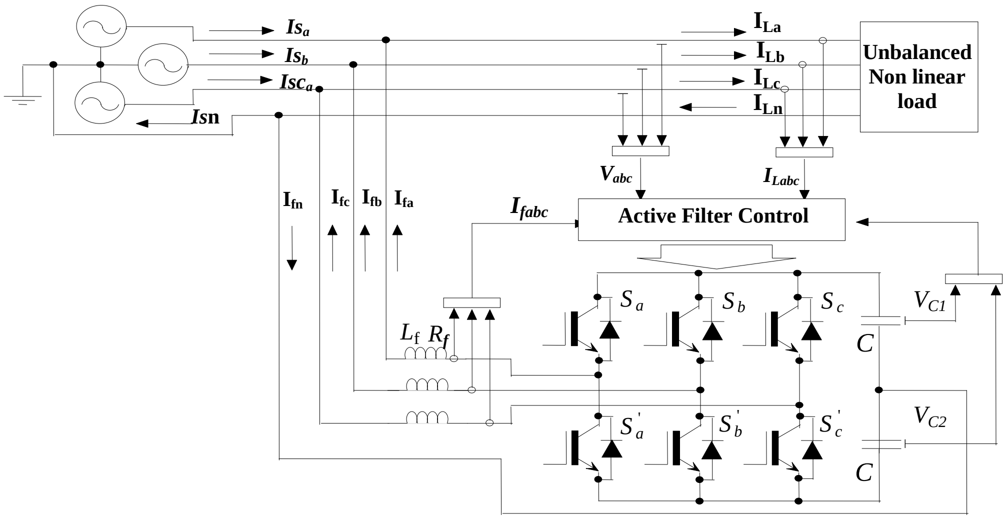

Figure 1. Three-Leg Converter ("Split-Capacitor" Inverter Topology)

The three leg inverter is preferred for its lower number of switching devices, while the construction of control circuit is complex, huge DC-link capacitors are needed and balancing the voltage of two capacitors is a key problem.

2.2. Four Leg Topology

A four-leg inverter (FLFB) is adopted to form the main circuit of active power filter (APF), its basic structure is shown in Figure 2. Eight power switches constitute four legs of a, b, c and n. Leg n offers a path, to zero sequence current from loads. There is no need for the dc link capacitor voltage balancing; the neutral current can be controlled independently of the phase currents. The four leg inverter has advantage to compensate neutral current by providing 4th-leg and need much less DC-link capacitance and has full utilization of DC-link voltage [8].

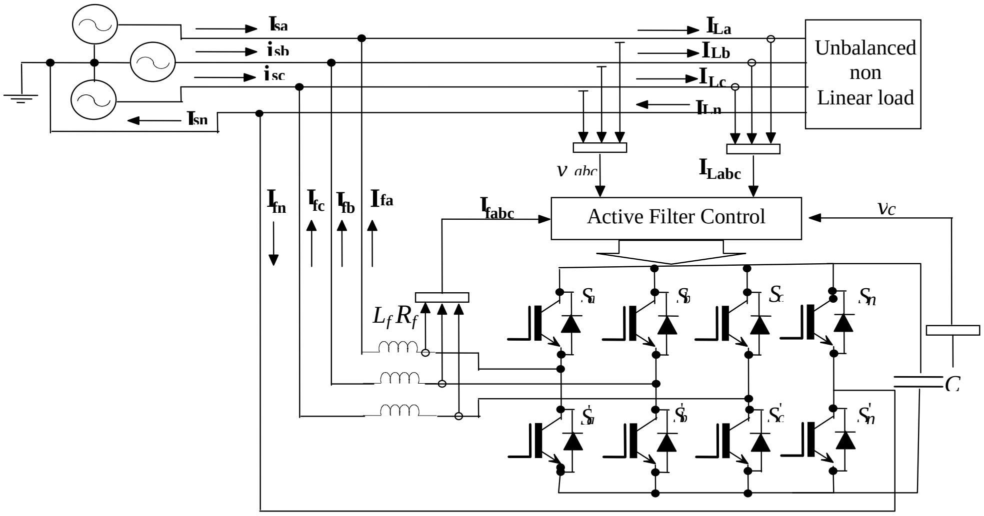

Figure 2. Four-Leg Converter (“Four Switch-Leg” Inverter Topology)

The following table contains comparison between three-leg split-capacitor topology (TLSC) components and four-leg inverter (FLFB) components.

Table 1. Components Comparison

	(FLFB)	(TLSC)
DC-link voltage sensors	1	2
IGBT switches	8	6
Number of gate drivers	8	6
DC-link capacitors quantity	1	2

The filter is based on an extension of the instantaneous power theory that considers the existence of zero-sequence phase current components in an unbalanced three phase four wire electrical distribution system.

3. Control Strategy

In 1983 Akagi proposed a new theory for the control of active filters in three-phase power systems called "Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as "Theory of Instantaneous Real Power and Imaginary Power", or "Theory of Instantaneous Active Power and Reactive Power", or "Theory of Instantaneous Power", or simply as "p-q Theory" was initially developed for three-phase three wire systems, with a brief mention to systems with neutral wire. Later, Watanabe and Aredes extended it to three-phase four-wire systems (systems with phases a, b, c and neutral wire) [9]. Since then it has become the most popular theory used for generating the compensating current reference for active power filters. It is applicable for both three phase three wire and three phase four wire active power filter [8].

In general concerning the phase-locked loop (PLL), the objective is to immunize it against the disturbances, more especially against the harmonic and the unbalances. PLL exports the sine and cosine signal circuit which produce sinusoidal signals in phase. Figure 3 presents an unbalanced supply voltage waveforms before using PLL, and figure 4 presents it after the use of PLL.

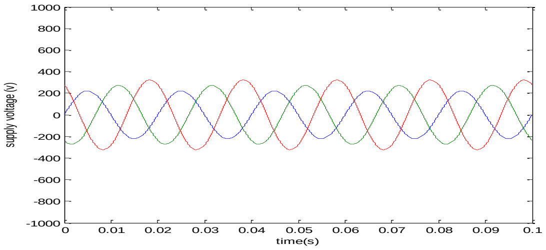

Figure 3. Supply Voltage Waveforms without PLL

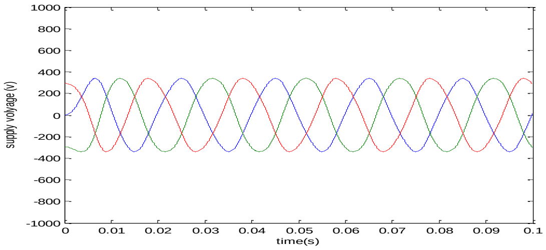

Figure 4. Supply Voltage Waveforms with PLL

This theory is based on a-b-c phase reference currents computation by transferring three phase voltage and current signal into corresponding α-β-0 components. Simply, the basic p-q theory consist of an algebraic transformation, known as Clarke transformation, of the sensed three-phase source voltage (V_{sa}, V_{sb}, V_{sc}) and load currents (I_{La}, I_{Lb}, I_{Lc}) from a-b-c coordinates to the α-β-0 coordinates is shown in (1) and (2) [10].

$$\begin{bmatrix} V_{\alpha} \\ V_{\beta} \\ V_{o} \end{bmatrix} = T \cdot \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_o \end{bmatrix} = T \cdot \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \tag{2}$$

Where

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{3}$$

Load side instantaneous real power ($P_{\alpha\beta}$), imaginary power ($q_{\alpha\beta}$) and zero sequence power (p0) are calculated as in (4).

$$\begin{bmatrix} P_0 \\ P_\alpha \\ P_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} V_0 & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{4}$$

Instantaneous real and imaginary powers include oscillating (AC) and average (DC) components as shown in (5). $P_{\alpha\beta}$ and $q_{\alpha\beta}$ may be, split into two parts (average values and oscillating values) as:

$$p_{net} = p_{\alpha\beta} + q_{\alpha\beta} + p_0 = \bar{p}_{\alpha\beta} + \tilde{p}_{\alpha\beta} + \bar{q}_{\alpha\beta} + \tilde{q}_{\alpha\beta} \tag{5}$$

After determining the active and reactive power signals, they are smoothened by passing through a low pass filter. Later, they are converted back to three phase reference currents and made available for comparison with actual currents.

$$\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_{s\alpha} \\ i^*_{s\beta} \\ i^*_0 \end{bmatrix} \tag{6}$$

4. Regulation of Capacitor Voltage

4.1. Proportional Integrator Controller

In many industrial applications, a PI controller is generally used to regulate the DC bus voltage of shunt active power filters. FLFB needs one proportional integrator controller however for TLSC two PI controllers are proposed. The regulation of the continuous voltage at the boundaries of the capacitor being ensured by a regulator made up of a low-pass filter of time constant and proportional regulator with Kc as a gain, which makes it possible to compensate losses in the inverter [7]. Since converter consumes an instantaneous active power given by:

$$Pc = \frac{d}{dt}\left(\frac{1}{2}CV_{dc}^{2}\right) \qquad (11)$$

For small change in Vdc* around its reference, this equation can be linearized as:

$$Pc = CV_{dc}\frac{d}{dt}\left(V_{dc}\right) \qquad (12)$$

For stabilizing the DC voltage, a proportional controller is used, response of it is calculated by:

$$\Delta V_{C12} = K_{p}\left(V_{c}^{*} - \left(V_{c1} + V_{c2}\right)\right) \qquad (13)$$

WhereV_{C1}, V_{C2} are voltages on capacitor C_1 and C_2, Kp gain of voltage controller, Vc* is DC voltage reference, where

$$C = K\left(1 - e^{-Ts/\tau}\right) \qquad (14)$$

$$d = -e^{Ts/\tau} \qquad (15)$$

In recurrence notation, we have:

$$P_{c}(K) = C\varepsilon(K-1) - dP_{C}(K-1) \qquad (16)$$

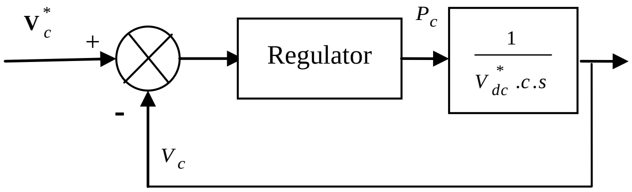

Figure 5. DC Voltage Control Bloc Diagram

4.2. Fuzzy Logic Control of DC-bus Voltage

The stability of the DC voltage determines the stability of the APF system. The regulation of the continuous voltage at the boundaries of the capacitor being ensured by a regulator made up of a low-pass filter of time constant and proportional regulator with Kc as a gain, which makes it possible to compensate losses in the inverter. In this section, the obtained error e (Vc*- Vc) and change of error signal are used as inputs for the fuzzy processing or fuzzy controller. Output of Fuzzy controller is reference current which is fed to PWM pulse generator [11].

Figure 6 shows a schematic block diagram of fuzzy inference system or fuzzy controller.

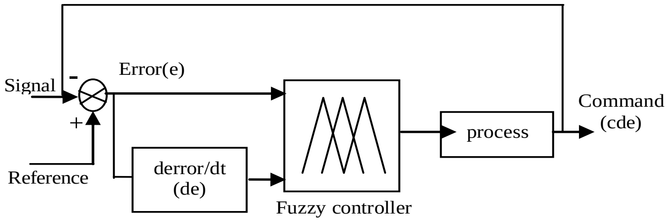

Figure 6. Fuzzy Inference System

Fuzzy logic controllers have generated a great deal of interest in certain applications. The advantages of fuzzy logic controllers are: robustness, no need to accurate mathematical model, can work with imprecise inputs, and can handle non-linearity [12].

Mamdani Fuzzy system has been used in the fuzzy controller. It is characterized for the following: - Seven fuzzy sets for each input - Seven fuzzy sets for the output - Triangular membership functions Defuzzyfication using the "centroid' method. The 49-rules used in this proposed controller are shown in Table 1.

Table 2. Rule Base Table

de	**NG**	**NM**	**NP**	**EZ**	**PP**	**PM**	**PG**
NG	NG	NG	NG	NG	NM	NP	EZ
NM	NG	NG	NG	NM	NP	EZ	PP
NP	NG	NG	NM	NP	EZ	PP	PM
EZ	NG	NM	NP	EZ	PP	PM	PG
PP	NM	NP	EZ	PP	PM	PG	PG
PM	NP	EZ	PP	PM	PG	PG	PG
PG	EZ	PP	PM	PG	PG	PG	PG

In three-leg split-capacitor topology (TLSC) two fuzzy logic controllers are implemented to control the DC-bus voltage but for four-leg inverter (FLFB) just one is realized.

5. Modulated Hysteresis Current Controller

Consider now the current controller with linear controllers using pulse width modulation (PWM) techniques, a constant switching frequency can be achieved and a well-defined harmonic spectrum can be obtained, but with limited dynamic properties.

Compared with linear controllers, non-linear ones based on hysteresis strategies allows faster dynamic response and better robustness with respect to the variation of the non-linear load. Nevertheless, with non-linear current controllers, the switching frequency is not constant and this technique generates a large side harmonics band around the switching frequency. To fix the switching frequency, one solution could consist in using a variable hysteresis bandwidth [13].

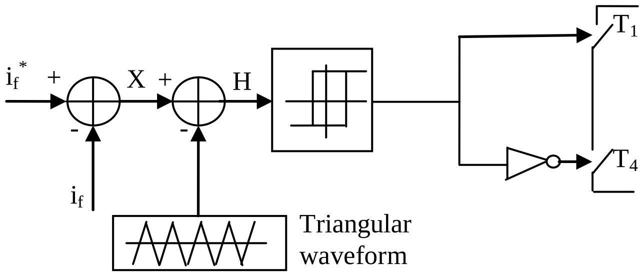

Figure 7. Modulated Hysteresis Current Controller

6. Comments of Results

The performance of the proposed method (fuzzy logic Controller for DC voltage) is examined with two different topologies of an active filter; three-leg split-capacitor topology

(TLSC) and four-leg inverter (FLFB). Results are compared with the conventional method. The dynamic response of the control strategy (and overall active power filter) is studied by switching three single phase inverter feeding unbalanced loads, and all simulations have been realized in the same conditions. The simulation results were carried out using Matlab under the following parameters:

Table 3. Parameters of Simulation

f=50Hz		
Vs1=220 v	Vs2=271 v	Vs3=322v
R_s=1,18e^{-3} Ω	L_s=37,6e^{-6}H	
R_c=4,3e^{-3} Ω	L_c=68,67e^{-6}H	
R_f=5e^{-2} Ω	L_f=1e^{-6}H	
R_{l1}=0,2 Ω	L_{l1}=1e^{-3}H	
R_{l2}=0,3 Ω	L_{l2}=2e^{-3}H	
R_{l3}=0,4 Ω	L_{l3}=3e^{-3}H	

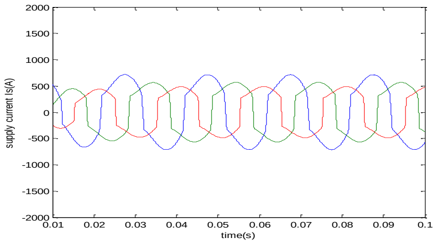

Figure 8.a Supply Current Waveform

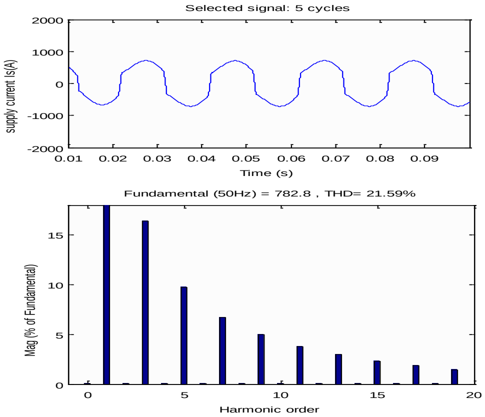

Figure 8.b Supply Current Waveform with THD

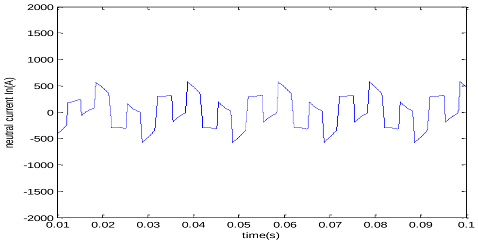

Figure 8.c Neutral Current Waveform

Figure 8. Waveforms Signal before Compensation

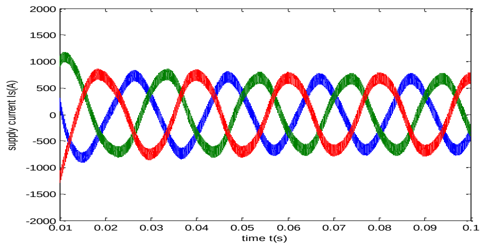

Figure 9.a Supply Current Waveform

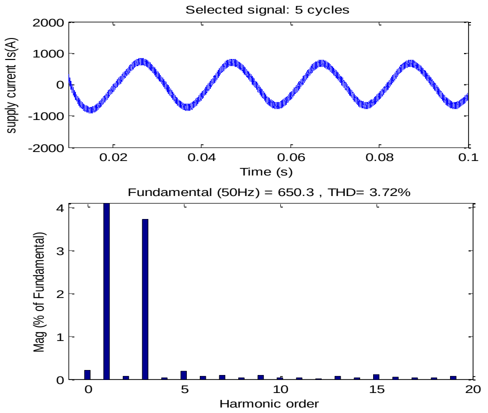

Figure 9.b Supply Current Waveform with THD

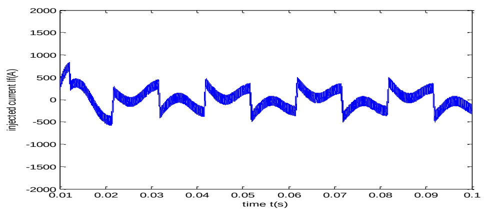

Figure 9.c Injected Current Waveform

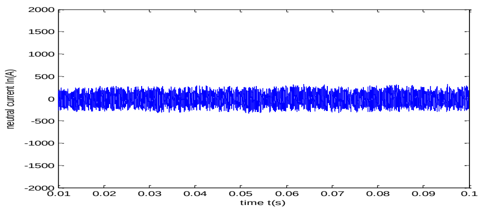

Figure 9.d Neutral Current Waveform

Figure 9. Waveforms Signal after Compensation (PI controller) (TLSC)

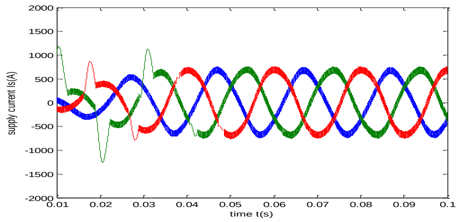

Figure 10.a Supply Current Waveform

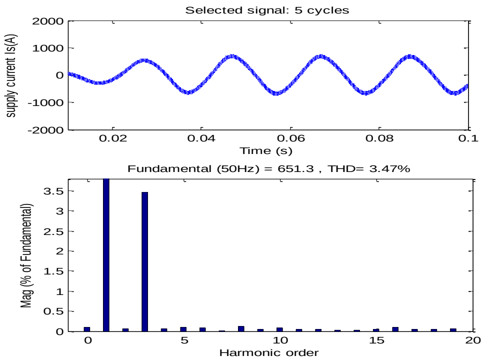

Figure 10.b Supply Current Waveform with THD

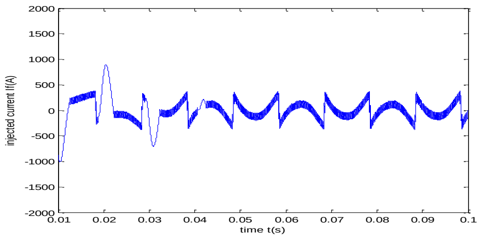

Figure 10.c Injected Current Waveform

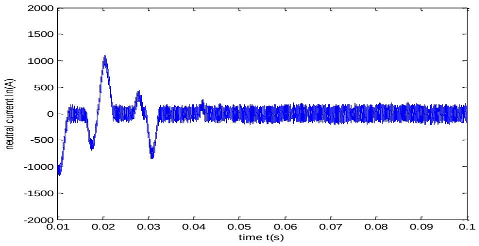

Figure 10.d Neutral Current Waveform

Figure 10. Waveforms Signal after Compensation (Fuzzy logic controller) (TLSC)

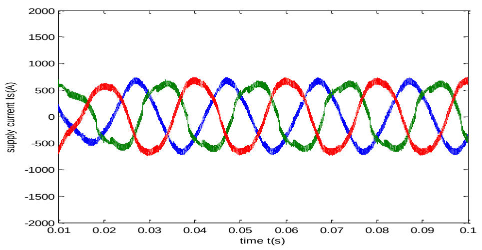

Figure 11.a Supply Current Waveform

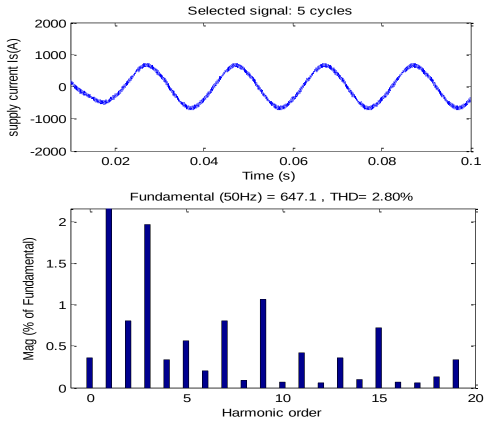

Figure 11.b Supply Current Waveform with THD

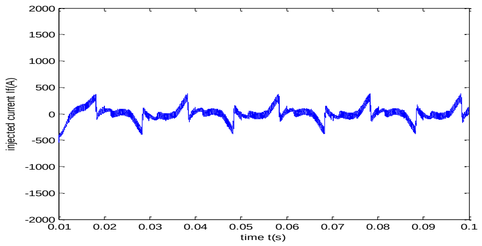

Figure 11.c Injected Current Waveform

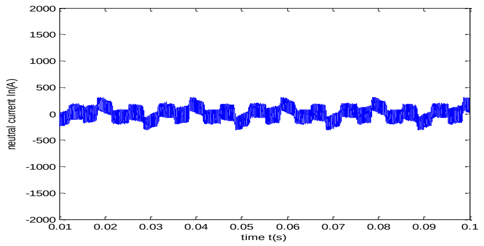

Figure 11.d Neutral Current Waveform

Figure 11. Waveforms Signal after Compensation (PI controller) (FLFB)

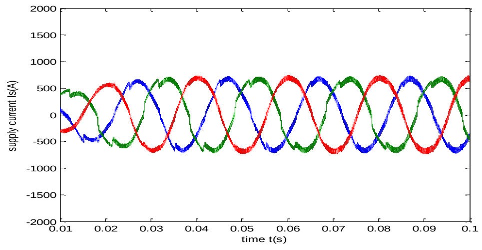

Figure 12.a Supply Current Waveform

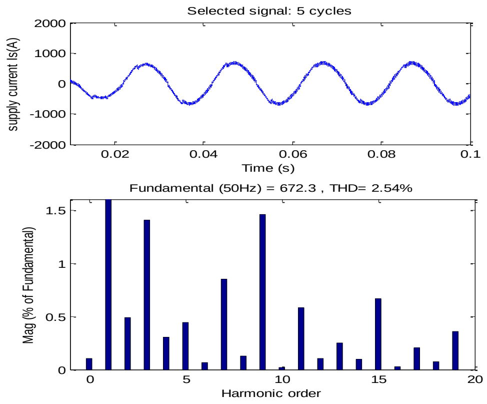

Figure 12.b Supply Current Waveform with THD

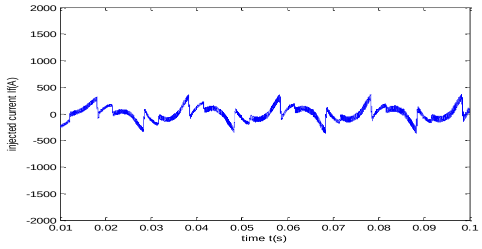

Figure 12.c Injected Current Waveform

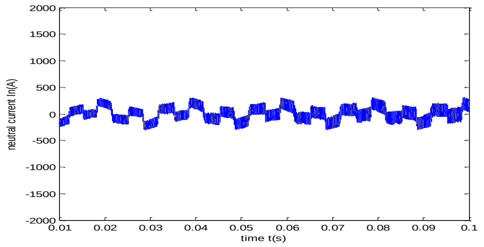

Figure 12.d Neutral Current Waveform

Figure 12. Waveforms Signal after Compensation (Fuzzy logic controller) (FLFB)

Waveforms signal illustrated in figure 8 show that the line currents before compensation are unbalanced with harmonics. As can be seen that the THD before compensation was 21,59%, and it becomes 3,72% with the PI controller and 3,47% using Fuzzy logic controller to regulate DC bus voltage in three leg topology (TLSC). Moreover the THD is 2, 80% with the PI controller and 2, 54% using Fuzzy logic controller to regulate DC bus voltage in four leg topology (FLFB). However as can be seen from fig.10.a and fig.11.a regarding the supply current waveform, it is quite difficult to appreciate the transient response for the different topologies. Hence, the total harmonic distortion THD is less than 5% for the two different topologies (TLSC and FLFB) which satisfy the CEI norms. Consequently, the obtained results have shown a better performance for four leg topology with fuzzy logic controller to regulate DC bus voltage.

7. Conclusion

Active filters for phase and neutral currents harmonic compensation in three phase four wire system feeding three single non-linear loads and fuzzy logic controller used in the regulation of the continuous voltage at the boundaries of the capacitor is proposed and compared with a proportional integral controller. This control algorithm provides that the DC bus voltage has been maintained as a constant value. So, the problem of the DC-bus voltage control in three-phase four-wire shunt active filter for two different topologies (TLSC and FLFB) is treated. The performance of the fuzzy logic control is verified through computer simulation. Therefore, the dc link fuzzy control has better dynamic behavior than conventional PI control strategy. Consequently, active power filters are capable to better compensate the current harmonics in three phase four-wire electrical networks.

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