Improvement of Power Quality Using Hybrid Power Filter with Fuzzy Logic Controller

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***Abstract*—In this paper, we present a Hybrid Power Filter (HPF) which consists of a combined system of Passive Filter (PF) and Series Active Power Filter (SAPF) has been designed by MATLAB/SIMULINK approach for harmonic and reactive power compensation. This filter is a three level PWM voltage source inverter and we use a Fuzzy Logic Controller (FLC) algorithm to control the harmonic voltages. The viability of the proposed algorithm is validated in this work. This combined system of filter is able to compensate the reactive power (showed that source voltage is sinusoidal and in phase with source current), and harmonics (voltage & current) for three phase of the non linear load current proposed with RL load. For the following voltage related problems in the power grid voltage flicker and voltage unbalance in three-phase systems are minimized under norm. The proposed solution has achieved an improvement of power quality in distribution system;**

***Index Terms*—active power filter, shunt passive power filter, power quality improvement, power factor, THD, fuzzy controller**

I. Introduction

Power Quality is defined as the extent to which both the utilization and distribution distresses the electric power system affects the efficacy of electrical equipment. These power harmonics are called electrical pollution which will degrade the quality of the power supply. As a result, filtering process for these harmonics is needed in order to improve the quality of the power supply. Therefore, these harmonics must be mitigating. In order to achieve this, series or parallel configurations or combinations of active and passive filters have been proposed depending on the application type [1], [2]. Conventionally passive filters were used to reduce the Total Harmonic Deduction (THD) and compensate the reactive power. Passive filters were considered to most reliable, cost effective, robust, and can be easily maintained. But they suffer from certain disadvantages like create resonance with the system, they are bulky and the most prominent is that they are tuned for particular harmonic frequency [3].

Since the beginning of the 1980s, active power filters (APFs) have become one of the most habitual compensation methods [4]. A usual APF consists of a three-phase Pulse Width Modulation (PWM) voltage source inverter. The APF can be connected either in parallel or in series with the load. The first one is especially appropriate for the mitigation of harmonics of the loads called harmonic current source. In contrast, the series configuration is suitable for the compensation of loads called harmonic voltage source. However, the costs of shunt active filters are relatively high for large-scale system and are difficult to use in high-voltage grids.

In addition, their compensating performance is better in the harmonic current source load type than in the harmonic voltage source load type [5].

II. Hybrid Power Filter Topology Descriptions and Modeling

A. Description of the HPF Topology

Fig. 1 shows the topology of the combined system of a series active power filter and shunt passive filter, acting as zero impedance for the fundamental frequency and as high resistor for the harmonics frequencies. The HPF, which is supplied by a low power PWM inverter, is connected in series with the main supply and the non-linear load through the current transformer. The passive filter connected in parallel to the load is used to damp the 5th and the 7th harmonic of V_l because of their high amplitudes.

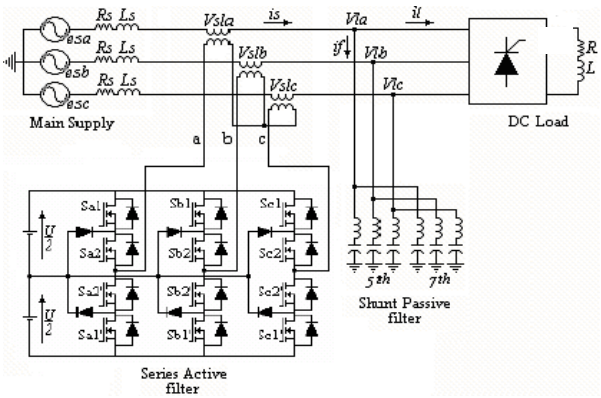

Figure 1. General configuration of a hybrid power filter

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The series APF acts as a voltage source and inject a compensating voltage in order to obtain a sinusoidal load voltage. The developments in digital electronics, communications and in process control system have made the loads very sensitive, requiring ideal sinusoidal supply voltage for their operation [5], [6].

B. Modeling

Fig. 2 shows the per-phase equivalent scheme of the studied topology.

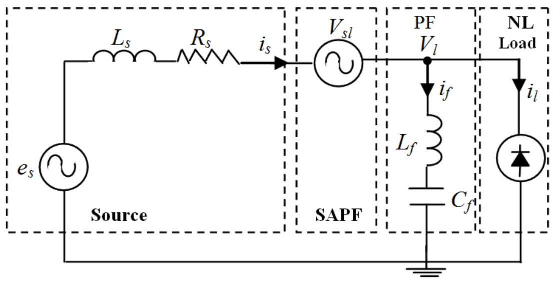

Figure 2. Per-phase equivalent scheme

where:

e_s, i_s, L_s, R_s: Source voltage, source current, source inductance, and source resistance,

V_s: Line voltage,

V_l, i_l: Load voltage and load current,

V_{sl}: Controllable voltage source representing the series active power filter,

i_f, C_f, L_f: Shunt passive filter current, passive filter capacitance, and passive filter inductance.

This equivalent scheme is modeled by (1) and (2):

$$V_{sl} = V_s - V_l \tag{1}$$

$$i_s = i_f + i_l \tag{2}$$

where:

$$V_s = e_s - (R_s \cdot i_s) - (L_s\ dt/di_s) \tag{3}$$

The voltage error is given by:

$$\Delta V_{sl} = V_{slref} - V_{sl} \tag{4}$$

V_{slref}: is expressed by:

$$V_{slref} = V_{sh} - V_{lh} \tag{5}$$

$$V_{sh} = k.\ i_{sh} \tag{6}$$

V_{sh}, V_{lh}, i_{sh}: represent, respectively, the harmonic components present in V_s, V_l, and i_s.

k: is a current sensor gain.

C. APF Voltage References Determination

The harmonic component V_{slh} of V_{sl} is defined by:

$$V_{slh} = V_{sl} - V_{slf} \tag{7}$$

First, we extract the p-q components of V_{sl} :

$$\begin{bmatrix} V_{slp} \\ V_{slq} \end{bmatrix} = C_{pq} C_{32} \begin{bmatrix} V_{la} \\ V_{lb} \\ V_{lc} \end{bmatrix} \tag{8}$$

C_{pq}, C_{32} representing the Park matrix and Concordia matrix given respectively by:

$$C_{pq} = \begin{bmatrix} \sin(\omega t) & -\cos(\omega t) \\ -\cos(\omega t) & -\sin(\omega t) \end{bmatrix} \tag{9}$$

$$C_{32} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{10}$$

Next, decomposition of V_{slp} and V_{slq} into continuous components $\overline{V}_{slp}$, $\overline{V}_{slq}$ and alternative components $\widetilde{V}_{slp}$, $\widetilde{V}_{slq}$

$$V_{slp} = \overline{V}_{slp} + \widetilde{V}_{slp} \tag{11}$$

$$V_{slq} = \overline{V}_{slq} + \widetilde{V}_{slq} \tag{12}$$

$\overline{V}_{slp}$, $\overline{V}_{slq}$ are obtained via a second order low-pass filter.

Then, the obtained three-phase fundamental components are presented below:

$$\begin{bmatrix} V_{slfa} \\ V_{slfb} \\ V_{slfc} \end{bmatrix} = C_{23} C_{pq}^{-1} = \begin{bmatrix} \overline{V}_{slp} \\ \overline{V}_{slq} \end{bmatrix} \tag{13}$$

Finally, this algorithm can be represented as shown in the block diagram of Fig. 3.

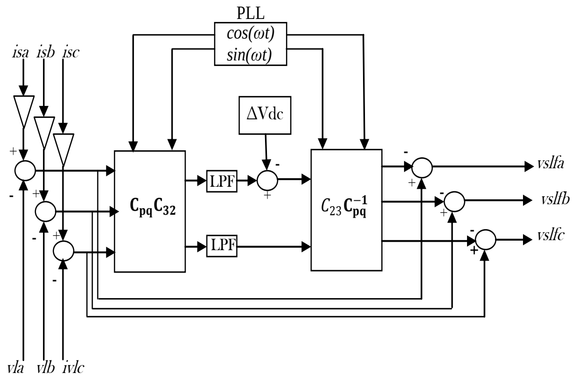

Figure 3. Block diagram of voltages references determination

D. Inverter Control Using PWM

The control method is aimed to control PWM inverter to produce the desired compensation voltage**,** in the output of series filter. This method is achieved by implementing a fuzzy logic controller [7]-[9] which starts from the difference between the injected voltage (V_{inj}) and the calculated reference voltage (V_{slf}) that determines the reference voltage of the inverter (modulating wave).

This reference voltage is compared with two carrying triangular identical waves shifted one from other by a half period of chopping producing the control signal to control the on-off of the IGBT [10], [11].

Fig. 4 shows the general block diagram of voltage control used.

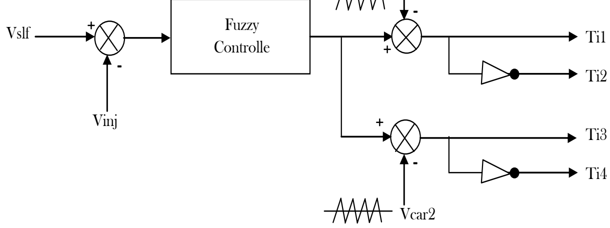

Figure 4. PWM synoptic block diagram of voltage control

The control of inverter arm constituting the series active filter is summarized in the two following steps.

- Determination of the intermediate signals V_{i1} and V_{i2}.

If error ≥ carrying 1 => $V_{i1} = 1$

If error < carrying 1 => $V_{i1} = 0$

If error ≥ carrying 2 => $V_{i2} = 0$

If error < carrying 2 => $V_{i2} = -1$

Determination of control signals of the switches T_{ij} (j = 1, 2, 3, 4).

If $(V_{i1}+ V_{i2}) = 1$ => $T_{i1} = 1, T_{i2} = 1, T_{i3} = 0, T_{i4} = 0$

If $(V_{i1}+ V_{i2}) = 0$ => $T_{i1} = 0, T_{i2} = 1, T_{i3} = 1, T_{i4} = 0$

If $(V_{i1}+ V_{i2}) = -1$ => $T_{i1} = 0, T_{i2} = 0, T_{i3} = 1, T_{i4} = 1$

E. Fuzzy Control Application

The FLC concept was proposed in 1965 that was based on a logical system called fuzzy logic. It is much closer in spirit to human thinking and natural language. FLC was deduced from fuzzy set theory. Fuzzy sets boundaries were undefined, ambiguous and useful for approximate systems design [12], [13]. FLC is used for the HPF in closed loop to control a constant DC voltage, improve the performance and reduce the *THD* of the current.

The (*e*) and its derivation (*de*) are used as inputs for fuzzy process.

Fig. 5 shows the synoptic scheme of fuzzy controller, which possesses two inputs (the error (*e*)).

($e = V_{slf} - V_{inj}$) and its derivative (*de*) and one output (the command (c_{de})). [9]

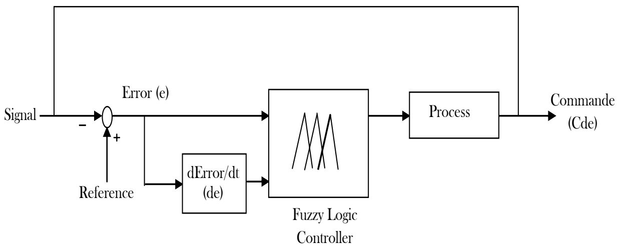

Figure 5. Fuzzy controller synoptic diagram

Mainly, the three main features of FLC are Fuzzification, Fuzzy Inference Mechanism (Knowledge base) and Defuzzification.

Fuzzification: The conversion process of a numerical variable to a linguistic variable.

Rule Elevator: FLC uses linguistic variables as a control gain. The basic operations of FLC requires AND (∩), OR) U (and NOT (~) for evaluation fuzzy set rules.

Defuzzification: The conversion process of linguistic variable to a numerical variable.

Database: stores the definition of the triangular membership function for the fuzzifier and defuzzifier.

Rule Base: stores the linguistic control rules required by rule evaluator. The 25 rules in this proposed controller are shown in Table I, is based on the error (*e*) sign, variation and knowing that (*e*) is increasing if its derivative (*de*) is positive, constant if (*de*) is equal to zero, decreasing if (*de*) is negative, positive if ($V_{slf} > V_{inj}$), zero if ($V_{slf} = V_{inj}$), and negative if ($V_{slf} < V_{inj}$), fuzzy rules are summarized in following table:

TABLE I. RULES BASE OF FUZZY CONTROL

C_{de}		***de***				
		BN	N	Z	P	BP
e	BN	*BN*	*BN*	*N*	*N*	*Z*
	N	*BN*	*N*	*N*	*Z*	*P*
	Z	*N*	*N*	*Z*	*P*	*P*
	P	*N*	*Z*	*P*	*P*	*BP*
	BP	*Z*	*P*	*P*	*BP*	*BP*

With: (BN): Big negative; (N): Negative; (Z): Zero (P): Positive and (BP): Big positive

Fig. 6 shows the membership Function of FLC used for the error ($e = V_{slf} - V_{inj}$) and its derivative (*de*), and one output (the command (c_{de}))

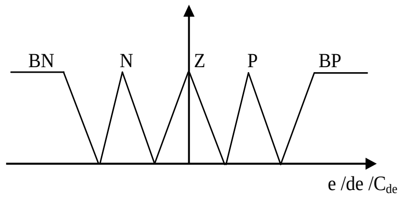

Figure 6. Membership function of FLC used

III. SIMULATION RESULTS

The simulation is carried out using a program working in MATLAB/SIMULINK environment. For non linear load we use a three phase diode rectifier with RL load.

The simulation parameters are shown in the Table II.

TABLE II. SYSTEM PARAMETERS

Source	e_s	230 V
	L_s	5,5 mH
	R_s	3,6 Ω
Load	R	25 Ω
	L	55 mH
Passive filter	L_{f5} ; C_{f5}	13,5 mH ;30 µF
	L_{f7} ; C_{f7}	6,75 mH ;50 µF
Turns Ratio of Coupling Transformer		1:1
Switching Frequency		10 KH
Current sensor gain k		5

A. Without Filtering

In Fig. 7 we present the waveform of the load current, load voltage; and the delay between voltage and current that represents the absorbed reactive power or power factor of the system.

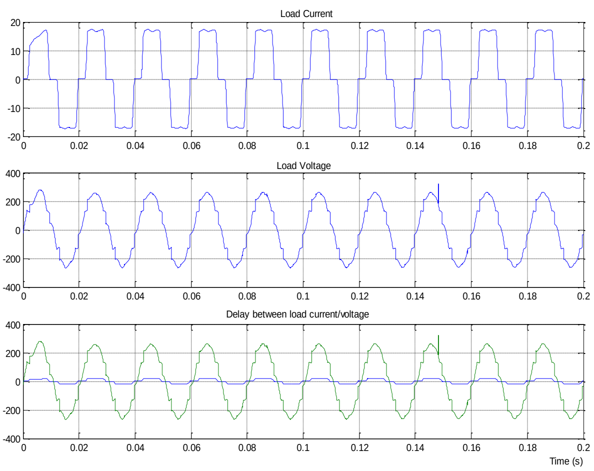

Figure 7. Waveforms of load (current, voltage), and their delay

Fig. 8 shows the waveform of the three voltages on the same graph. In this figure we see that there are disruptive phenomena appear as flicker and voltage imbalance.

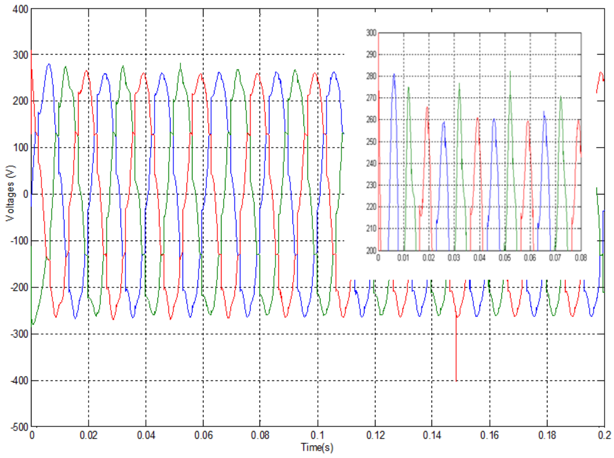

Figure 8. Voltages loads

Fig. 9 shows the harmonic spectrum of current without filtering.

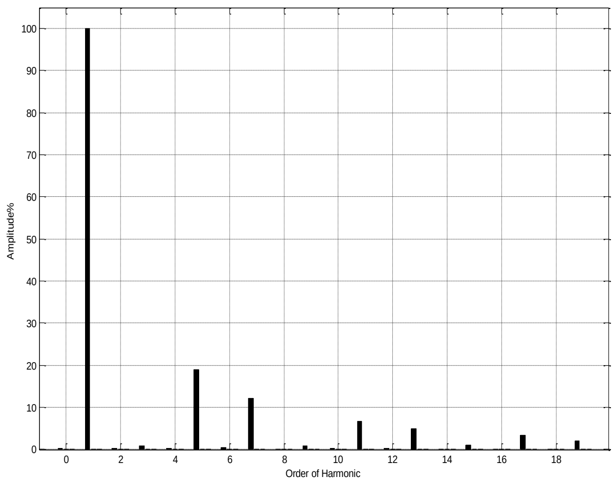

Figure 9. Harmonic spectrum of current

The harmonic spectrum of current shows that the harmonics of order 5, 7, 11, 13 ...; are the most predominant harmonic and have larger amplitudes; because they are harmonics characteristics (following relationship 6K ±1; k is an integer number); and return to the non linear load used (Three phase rectifier PD3).

B. *With Passive Filter (PF) Only*

The simulations results with passive filter only are presented in Fig. 10, Fig. 11 and Fig. 12.

Fig. 12 shows the harmonic spectrum of current with passive filter only.

After the use of the passive filtering (two resonant filter to rank harmonics 5 and 7); we clearly see the elimination of the current harmonics of order 5 and 7.

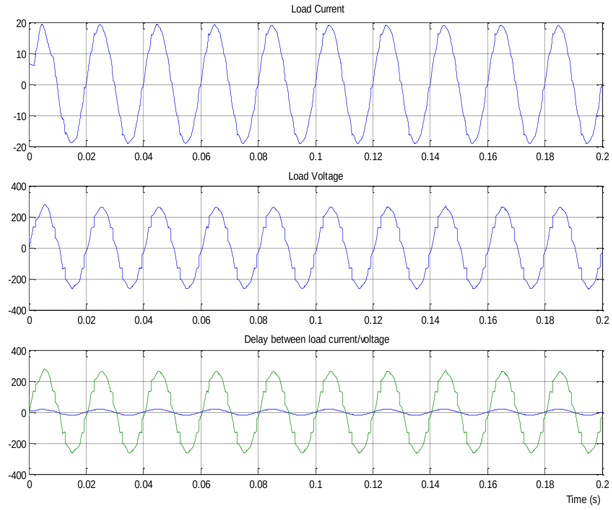

Figure 10. Waveforms of sources (current, voltage), and their delay with PF only

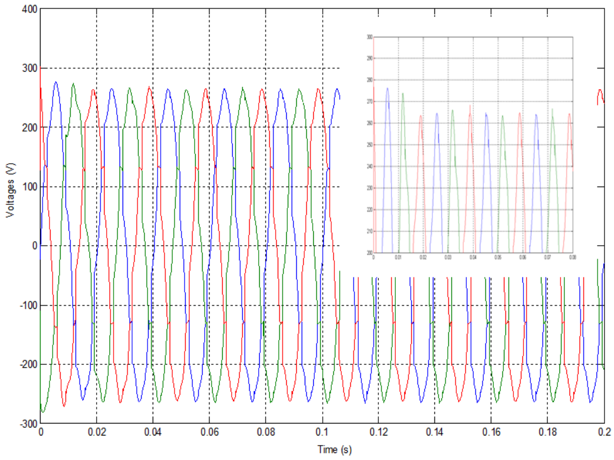

Figure 11. Voltages sources with PF only

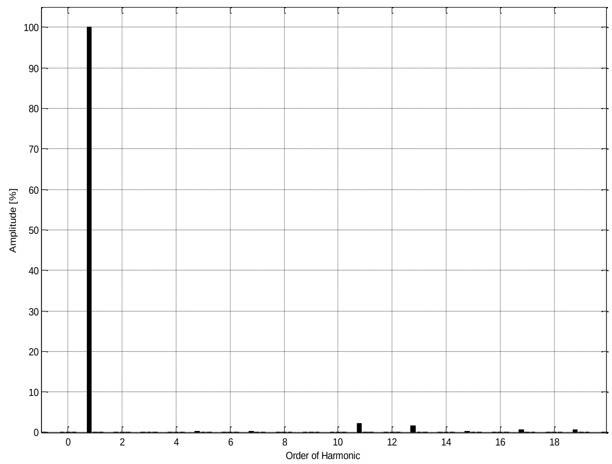

Figure 12. Harmonic Spectrum of current with PF only

C. *With Hybrid Power Filter (HPF)*

The simulations results after filtering by using hybrid power filter are presented in Fig. 13-Fig. 16.

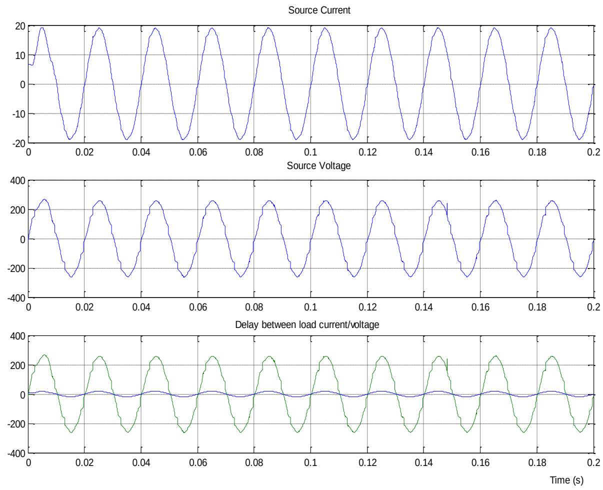

Figure 13. Waveforms of sources (current, voltage), and their delay with HPF

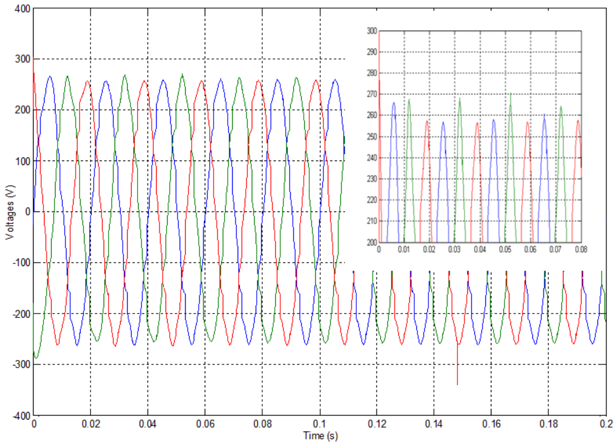

Figure 14. Voltages sources with HPF

Fig. 15 shows the waveform of the injected voltage by the series active series filter.

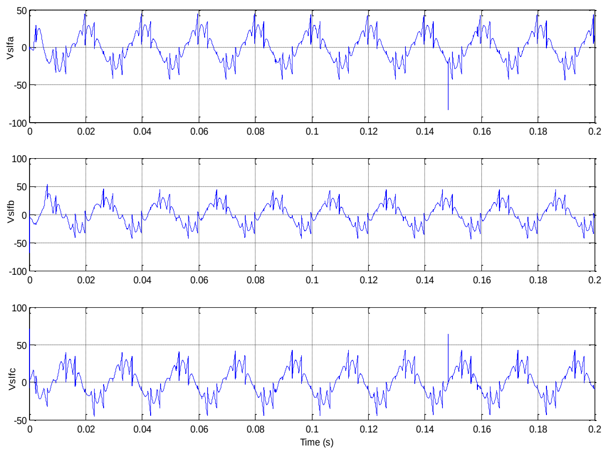

Figure 15. Voltages references of active series filter

Fig. 16 shows the Harmonic Spectrum of current with Hybrid Power filter.

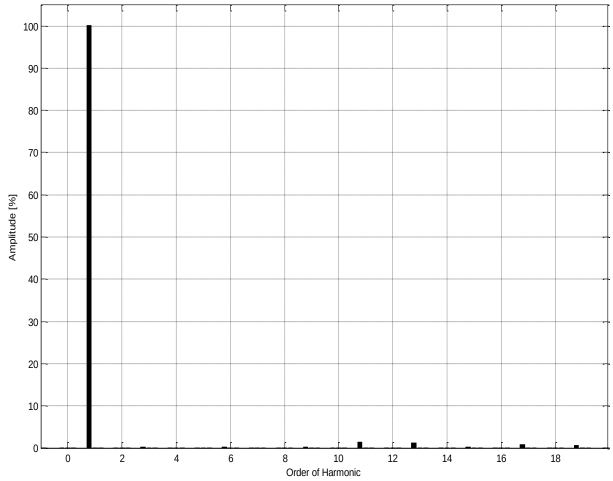

Figure 16. Harmonic spectrum of current with HPF

In Table III and Table IV we present the simulations results before and after filtering for currents and voltages harmonics.

TABLE III. SIMULATION RESULTS OF HARMONICS CURRENTS

Harmonic Currents	Without	With PF Only	With HPF
5	19,00 %	0,26 %	0,19 %
7	12,29 %	0,32 %	0,03 %
11	6,63 %	2,19 %	1,54 %
13	4,93 %	1,74 %	1,27 %
17	3,35 %	0,71 %	0,97 %
19	2,03 %	0,77 %	0,59 %
THDi	**24,46** %	**3,40** %	**2,19** %

TABLE IV. SIMULATION RESULTS OF HARMONICS VOLTAGES

Harmonic Voltages	Without	With PF Only	With HPF
5	1,14 %	0,85 %	0,67 %
7	0,48 %	0,76 %	0,28 %
11	4,08 %	3,42 %	2,42 %
13	3,34 %	2,77 %	1,94 %
17	2,12 %	3,50 %	1,29 %
19	1,88 %	2,03 %	1,07 %
THDv	**7,49 %**	**6,74 %**	**4,27 %**

It summarizes in the Table V; harmonic minimization rate with the use of only passive filtering (PF) and hybrid Power filtering (HPF).

TABLE V. EFFICIENCY OF THE FILTERS USED

	Harmonics Currents		Harmonics Voltages	
	With PF Only	With HPF	With PF Only	With HPF
5	98,63 %	99 %	25,44 %	41,23 %
7	97,4 %	97,67 %	58,33 %	41,67 %
11	68,33 %	76,77 %	16,18 %	40,68 %
13	64,71 %	74,24 %	17,06 %	41,92 %
17	78,81 %	71,04 %	65,09 %	39,15 %
19	62,07 %	70,94 %	7,98 %	43,08 %
THD	86,1 %	**91,05 %**	10,01 %	**36,98 %**

IV. DISCUSSIONS

After the simulation results, we note that with the use of passive filtering (Filter 5 and 7) that there a total elimination of harmonic 5^{th} and 7^{th} which have large amplitudes; The harmonic 5 is reduced from 19% to 0,26% with rate of 98,63%; the harmonic 7 from 12,29% to 0,32% with rate of 97,4% and for the current THD is reduced from 24,46% to 3,40% with rate 86,1% For the voltage THD is reduced from 7, 49% to 6,74% with rate of 10,01%

The obtained results for hybrid filter showed clearly that the use of is better than utilization of passive filter only especially for mitigation of voltages harmonics from 7,49% to 4,27 with rate of 36,98% under norm (5%). and the same for the current THDI from 24,46% to 2,19% (Under Standard) with rate of 91,05% [14].

In Fig. 7 shows the delay between current and source voltage is big but the Fig. 13 illustrates the delay reduction between source current and voltage; i.e. power factor correction when the hybrid filter is connected.

In Fig. 8 we see that it to be disruptive phenomena associated with voltage as imbalance and flicker and after use a Hybrid Filter we note that these phenomena are reduced (Fig. 14) and this because the injected voltage by this filter.

V. CONCLUSION

In this paper we have presented the three-phase hybrid active power filter for compensation of harmonic currents generated by the non-linear load. The fuzzy logic control based HPF for three-phase system is modeled and simulated in MATLAB/SIMULINK environment. The main objective of this research work has been accomplished.

The total harmonic distortion of the supply current and voltage has been decreased at a high level in the simulation. Which is an achievement to meet the IEEE 519 recommended harmonic standard. In fact, not only the harmonics were reduced to an acceptable rate, but also the transient response time was minimized. Moreover, the utility power factor was corrected, unbalanced voltage and flicker is minimized.

REFERENCES

[1] B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement," *IEEE Trans. Ind. Electron.*, vol. 46, no. 5, pp. 960–971, Oct. 1999.

[2] H. K. Chiang, B. R. Lin, K. T. Yang, and K. W. Wu, "Hybrid active power filter for power quality compensation," in *Proc. EEEE PEDS*, 2005, pp. 950-954.

[3] B. R. Lin, H. K. Chiang, and C. H. Huang, "Three-phase three level active power filter with a clamped capacitor topology," *IEE Proceedings-Electric Power Applications*, vol. 153, pp. 513–522, July 2006.

[4] R. S. Herrera and P. Salmerón, "Instantaneous reactive power theory: A comparative evaluation of different formulations," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 595–604, Jan. 2007.

[5] H. Yang and S. Ren, "A practical series-shunt hybrid active power filter based on fundamental magnetic potential self-balance," *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2089–2096, Oct. 2008.

[6] S. George and V. Agarwal, "Optimum control of selective and total harmonic distortion in current and voltage under non sinusoidal conditions," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 937–944, Apr. 2008

[7] M. Suresh, A. K. Panda, and S. Yellasiri, "Fuzzy controller based 3phase 4wire shunt active Filter for mitigation of current harmonics with combined p-q and Id-Iq control strategies," *Journal of Energy and Power Engineering*, vol. 3, no. 1, pp. 43-52, 2011.

[8] Y. Djeghader and L. Zellouma, "Using hybrid power filter to mitigate currents and voltages harmonics in three phase system," *Acta Electrotechnica et Informatica*, vol. 15, no. 4, pp. 37-43, 2015.

[9] S. Saad and L. Zellouma, "Fuzzy logic controller for three-level shunt active filter compensating harmonics and reactive power," *Electric Power Systems Research*, vol. 79, pp. 1337–1341, 2009.

[10] B. Ning and Z. Zhang, "Comparison of Total ionizing dose effects for floating and tied body SOI MOSFETs," *International Journal of Electronics and Electrical Engineering*, vol. 1, no. 1, March 2013.

[11] P. Nguyen and M. Han, "The investigation of equivalent harmonic impedances of VSC-based HVDC systems," *International Journal of Electronics and Electrical Engineering*, vol. 4, no. 1, February 2016.

[12] S. Lalouni and D. Rekioua, "Modeling and simulation of a photovoltaic system using fuzzy logic controller," in *Proc. Second International Conference on Developments in e Systems Engineering*, 2009, pp. 23-28.

[13] S. Kerrouche and F. Krim, "Three-phase active power filter based on fuzzy logic controller," *International Journal of Sciences and Techniques of Automatic Control& Computer Engineering*, vol. 3, no. 1, pp. 942-955, July 2009.

[14] Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, The Institute of Electrical and Electronics Engineers, IEEE Standard 519-1992, 1993.

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