Three-Level Series Active Power Filter

L. Zellouma and S. Saad

Laboratoire des Systèmes Electromécaniques, University of Badji Mokhtar-Annaba-Algeria
Emails: zellouma13@yahoo.fr, saadsalah2006@yahoo.fr

Abstract — **In this paper, the three-level inverter is used as a series active power filter, making use of the multilevel inverter advantages of less total harmonic distortion and reduced semiconductor ratings. This filter is a three level PWM voltage source inverter used to suppress harmonic voltage drawn from a nonlinear load and acts as zero impedance for the fundamental frequency and as high resistor for harmonic frequencies. Most previously reported three-phase series active power filters are based on two-level inverters with conventional controllers requiring a complex and a complicated mathematical model. In order to overcome this problem a fuzzy logic controller is used and extended to a three level SAPF.**

This work presents principles of operation and design of a fuzzy logic controller algorithm to control the harmonic voltages. The viability of the proposed algorithm is validated with computer simulation. The obtained results showed that source voltage is sinusoidal and in phase with source current. The proposed solution has achieved a low total harmonic distortion demonstrating the effectiveness of the presented fuzzy logic control algorithm.

Keywords — **Active power filter, passive power filter, power quality compensator, fuzzy controller, conventional controller.**

1 – Introduction

Power quality deterioration generally results from the intensive use of static converters and other non-linear loads. The reduction of the harmonic and reactive currents becomes an increasingly required issue. Passive LC filters have been used [1] to remove line current harmonics and to improve the power factor. However, when implemented, these passive filters present many drawbacks such as tuning problems, series and parallel resonance.

Recently active power filters have been widely used, studied and presented as a solution to harmonic problems. These filters are classified into shunt active power filter, injecting compensating currents [2,3,4,5]; the series active power filter, injecting compensating voltages through a transformer [2,3,6,7]; the hybrid filters (parallel passive filters and series active power filter) [8,9] acting as zero impedance for the fundamental frequency and as high resistor for harmonics frequencies and finally, Unified Power Quality Conditioner UPQC (series active power filter and shunt active power filter) compensating supply voltage and load current [10].

The series active power filter is appropriate for compensating harmonic voltage source, which has sufficient capacitance component in the DC link of the rectifier. In particular, the solution for harmonic voltage source is critical because the loads that act as harmonic voltage sources, such as copiers, fax machines, fluorescent lamps, air conditioners etc., have continued to increase.

Therefore, a hybrid filter topology has been developed achieving the desired damping performance with a significant reduction in the kVA-rating required by the power shunt active filter [8,9].

Active power filter implemented with two levels voltage source inverters have been widely studied and used to eliminate harmonics. Due to power handling capabilities of power semi-conductors, these active power filters are limited in medium power applications. Hybrid topologies shunt passive filter and series active filter were proposed to achieve high power filters.

Recently, there has been an increasing interest in using multilevel inverters for high power drives, reactive power and harmonics compensation [11,12,13,14,15]. Multilevel pulse width modulation inverters can be used as series active power filter for high power applications solving the problem of power semiconductor limitation. The use of neutral-point-clamped (NPC) inverters allows equal voltage shearing of the series connected devices in each phase.

Most previously reported three-phase series active power filters are based on two-level inverters with conventional controllers requiring a complex and a complicated mathematical model.

This paper presents a three level series active power filter implemented with a three level NPC voltage source inverter. A fuzzy logic controller is proposed to control the harmonic voltage in three level series active power filter.

The PWM technique [16] is employed to generate the inverter switching signals and *p-q* theory [17,18] for harmonic voltage identification.

A SIMPOWERSYSTEM Matlab /simulation model based on proposed control strategy is given and the simulation results are discussed.

2- Series APF topology description and modeling

A- Description of the APF Topology

Fig.1, shows the topology of the combined series APF and shunt passive filter, acting as zero impedance for the fundamental frequency and as high resistor for the harmonics frequencies.

The APF, 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 *Vl* because of their high amplitudes.

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.

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It can be found out from the analysis of the process of operation principle that the simultaneous and accurate acquisition of reference voltage signal is very important. In this paper a fuzzy logic controller is proposed as a solution to improve the compensating harmonic voltages.

The control method is aimed to control a PWM inverter to produce the desired compensating voltage, in the output of the series APF.

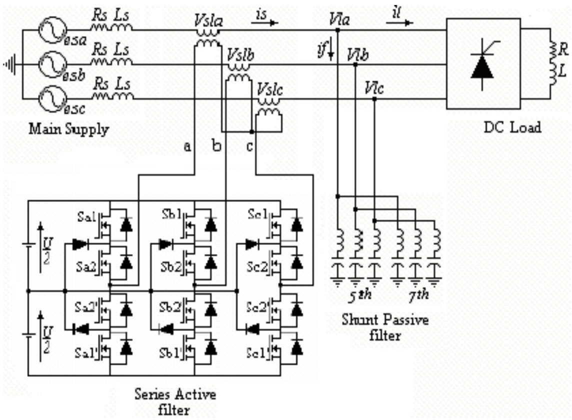

Fig.1. General Configuration of hybrid active power filter

b- Modelling

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

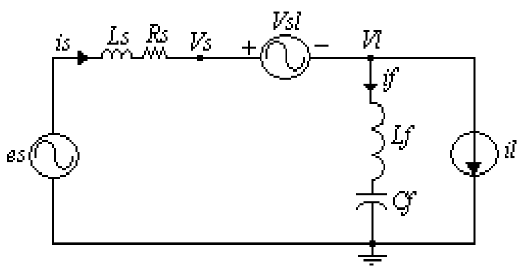

Fig.2. Per-phase equivalent scheme.

Where:
es, is, Ls, Rs: source voltage, source current, source inductance, and source resistance,
Vs: line voltage,
Vl, il : load voltage and load current,
Vsl: controllable voltage source representing the series active power filter,
if, Cf, Lf: shunt passive filter current, passive filter capacitance, and passive filter inductance.

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

$$Vsl = Vs - Vl \quad (1)$$

$$is = if + iL \quad (2)$$

Where,

$$Vs = es - Rs \cdot is - Ls\frac{dis}{dt} \quad (3)$$

The voltage error is given by:

$$\Delta Vsl = Vslref - Vsl \quad (4)$$

Vslref is expressed by:

$$Vslref = Vsh - Vlh \quad (5)$$

$$Vsh = k.\, ish \quad (6)$$

Vsh, Vlh, ish: represent, respectively, the harmonic components present in *Vs, Vl,* and *is*.
k: is a current sensor gain.

3- APF voltage references determination

The harmonic component *Vslh* of *Vsl* is defined by:

$$Vslh = Vsl - Vslf \quad (7)$$

First, we extract the *p-q* components of *Vsl*:

$$\begin{bmatrix} Vslp \\ Vslq \end{bmatrix} = Cpq.C32 \begin{bmatrix} Vsl_a \\ Vsl_b \\ Vsl_c \end{bmatrix} \quad (8)$$

Cpq, *C*32 representing the Park matrix and Concordia matrix given respectively by:

$$Cpq = \begin{bmatrix} sin(\omega t) & -cos(\omega t) \\ -cos(\omega t) & -sin(\omega t) \end{bmatrix}$$

$$C32 = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}$$

Next, decomposition of *Vslp* and *Vslq* into continuous components $\overline{V}slp$, $\overline{V}slq$ and alternative components $\tilde{V}slp$,$\tilde{V}slq$:

$$Vslp = \overline{V}slp + \tilde{V}slp \quad (9)$$

$$Vslq = \overline{V}slq + \tilde{V}slq \quad (10)$$

$\overline{V}slp$, $\overline{V}slq$ are obtained via a second order low-pass filter.
Then, the obtained three-phase fundamental components are presented below:

$$\begin{bmatrix} Vslf_a \\ Vslf_b \\ Vslf_c \end{bmatrix} = C23.\, Cpq^{-1}\begin{bmatrix} \overline{V}slp \\ \overline{V}slq \end{bmatrix} \quad (11)$$

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

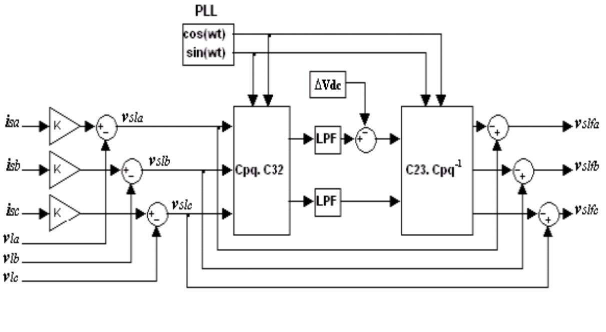

Fig.3. Block diagram of voltages references determination

4 – Inverter control using PWM

The control method is aimed to control PWM inverter to produce the desired compensation voltage, in the output of series APF. This method is achieved by implementing a fuzzy logic controller [19,20,21] 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. The general block diagram of voltage control is shown in Fig.4.

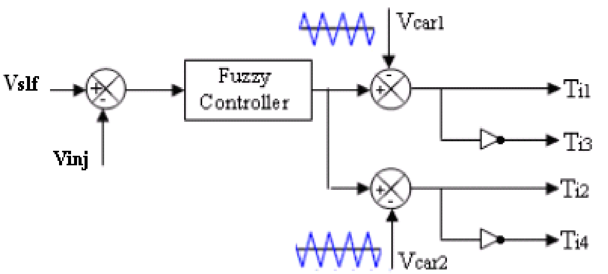

Fig.4. PWM synoptic block diagram of voltage control

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

5 – Fuzzy Control Application

Fuzzy logic serves to represent uncertain and imprecise knowledge of the system, whereas fuzzy control allows taking a decision even if we can't estimate inputs/outputs only from uncertain predicates. Fig. 5, shows the synoptic scheme of fuzzy controller, which possesses two inputs (the error (*e*), (*e = Vslf –Vinj)* and its derivative (*de*)) and one output (the command (*cde*)).

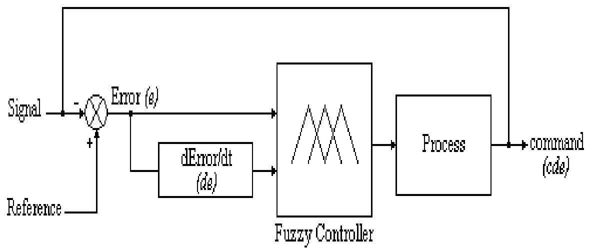

Fig.5. Fuzzy controller synoptic diagram

The objective is to obtain a sinusoidal source currents (and load voltages) in phase with the supply voltages at the common coupling point. This step consists on replacing the conventional controllers (P, PI…) by fuzzy logic controllers. The fuzzy controller algorithm is designed as follows:

- Three fuzzy sets for each input (*e*, *de*) with Gaussian membership functions,
- Five fuzzy sets for the output with triangular membership functions,
- Implications using the 'minimum' operator, inference mechanism based on fuzzy implication containing five fuzzy rules,
- Defuzzyfication using the 'centroïd' method.

The establishment of the fuzzy rules illustrated in Fig.6, 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 (*Vslf* > *Vinj*), zero if (*Vslf* = *Vinj*), and negative if (*Vslf* < *Vinj*), fuzzy rules are summarized as following:

1. If (*e*) is zero (Z), then (*cde*) is zero (Z).
2. If (*e*) is positive (P), then *(cde)* is big positive (BP).
3. If (*e*) is negative (N), then (*cde*) is big negative (BN).
4. If (e) is zero (Z) and (de) is positive (P), then (*cde*) is negative (N).
5. If (e) is zero (Z) and (de) is negative (N), then (*cde*) is positive (P).

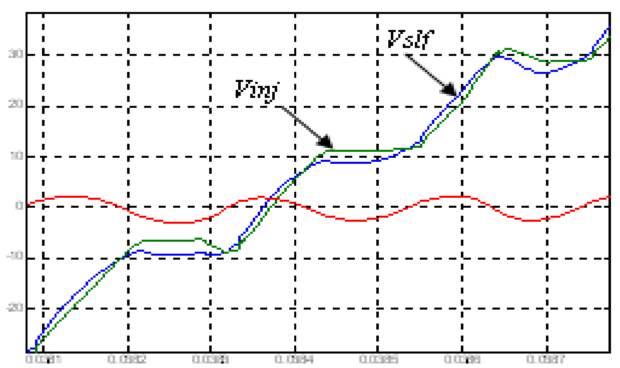

Fig.6 Fuzzy rules establishment

6 – Simulation

The simulation is carried out using a program working in MATLAB Simulink environment. The simulation parameters are given in table.1, presented below.

Table.2. Simulation Parameters

Supply: *Vs*, *Rs*, *Ls*	220 V, 0.01Ω, 0.1 mH.
DC Load: *Rdc*, *Ldc*	10 Ω , 2 mH
DC supply voltage U	1000 V
Fifth harmonic filter Cf, Lf Seventh harmonic filter Cf, Lf	3.3 mH, 120 μ F 11 mH, 18 μ F
Switching frequency	10 K Hz
Current sensor gain k	5

The obtained switching signals of the three-phase three-level inverter are shown in the Fig.7.

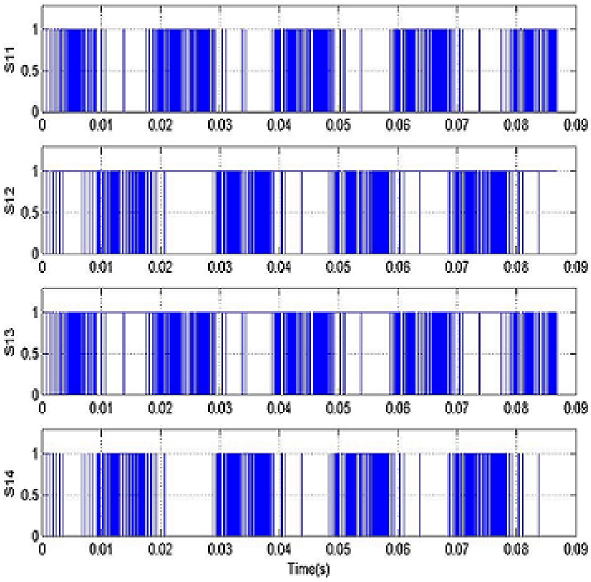

Fig. 7. Switching pulses of APF arm (S11, S12, S13, , S14)

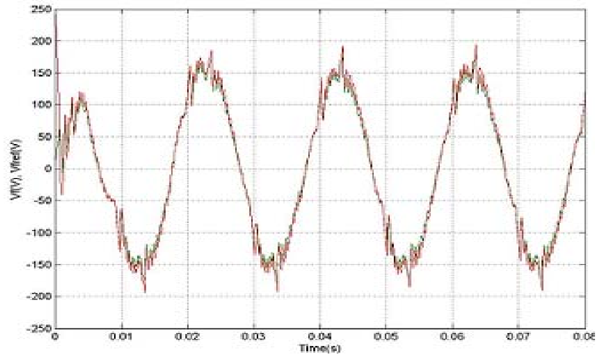

Fig.8. APF voltage output *Vsl* and its reference *Vslf*.

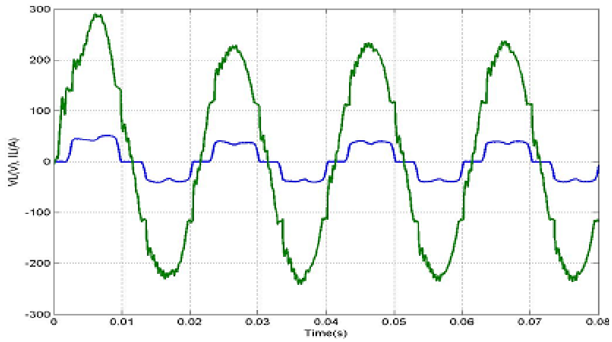

Fig. 9. Delay between Source current/voltage is_a and Vs_a.

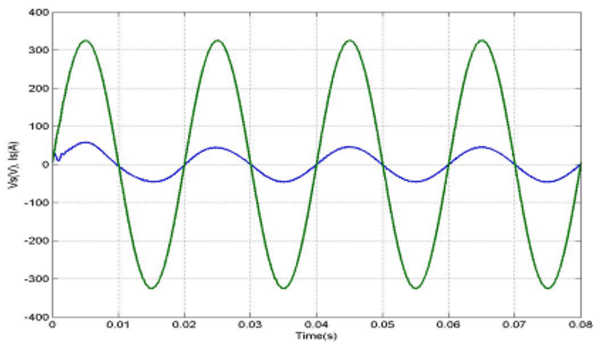

Fig. 10. Delay reduction between Source current/voltage is_a and Vs_a and power factor correction.

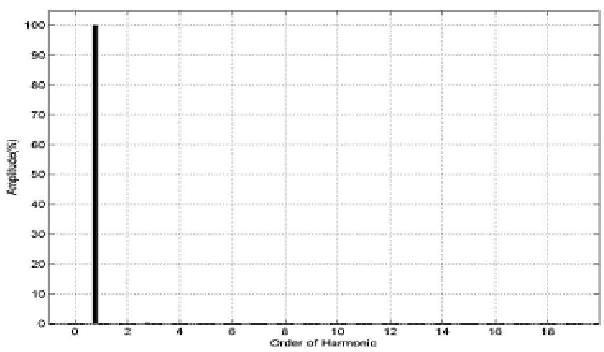

Fig.11. Source voltage spectrum when the filter is connected

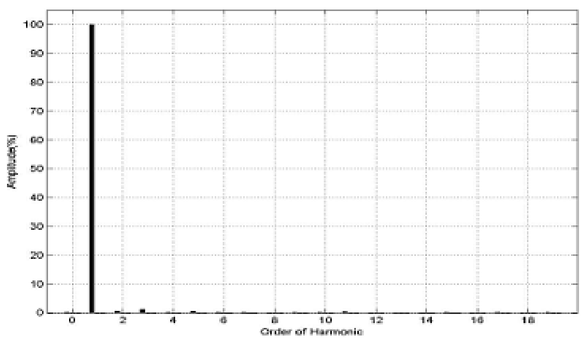

Fig. 12. Source current spectrum when the filter is connected

7- Results and discussions

To evaluate the performance of the proposed hybrid active power filter, the system specifications and passive harmonic filter parameters are given in table 1. Also, values of sensor current gain K= 5, the switching frequency is 10Khz. The three-phase source voltages are assumed to be balanced and sinusoidal. The active filter voltage output of the phase-a is shown in Fig. 8. A load with highly nonlinear characteristics is considered for the load compensation.

Fig. 9 shows the delay between source current and source voltage (is_a and *Vs*). Fig. 10, illustrates the delay reduction between Source current/voltage is_a and Vs_a and power factor correction when the hybrid filter is connected. The Fig.11 and 12, show the source voltage spectrum and the current source spectrum when the hybrid power active filter is connected (THD i_{sa} is reduced from 24,64 % to 2 %).

Simulation results show that presented hybrid active power filter reduces THD percentage to 2 percent which is ideal for power network and also transient response is around 0.01s.

8 - Conclusion

The goal of this work is to show the advantages of the multilevel series active filter when using fuzzy logic controllers instead of conventional controllers. 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.

The fuzzy logic controller has improved the steady state performance of series active power filter. The effectiveness of the proposed scheme is proved by simulation.

References

[1] J. C. Das, Passive Filters—Potentialities and Limitations, IEEE Transactions on Industry applications, Vol. 40, No. 1, FEBRUARY 2004, pp 232-241.
[2] H. Akagi, “Trend in Active Power Line Conditioners”, in IEEE Trans. On Ind. Electronics, Vol.9, N°3, August 1994, pp. 263-268.
[3] Salem Rahmania, Kamal Al-Haddad a, Hadi Youssef Kanaan, A comparative study of shunt hybrid and shunt active power filters for single-phase applications: Simulation and experimental validation, Elsevier, Mathematics and Computers in Simulation 71 (2006) 345–359.
[4] S. GH. Seifossadat, R. Kianinezhad, A. Ghasemi, M. Monadi, “Quality Improvement of Shunt Active Power Filter, Using Optimized Tuned Harmonic Passive Filters” SPEEDAM 2008 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, IEEE, 2008, pp 1388- 1393.
[5] A.M. Massoud, S.J inney, D.M. Grant, B.W. Williams, Predictive Current Controlled Shunt Active Power Filter Using Three-level Cascaded Type Inverter, IEEE IET International Conference, March 2006, pp 388 – 393.
[6] G.-Myoung Lee, Dong-Choon Lee, and Jul-Ki Seok, Control of Series Active Power Filters Compensating for Source Voltage Unbalance and Current Harmonics, IEEE Transactions on Industrial Electronics, Vol. 51, No. 1, February 2004, pp 132-139.
[7] Hai Lan, Jincheng Liang, Weiping Wu, Research of Harmonic Detection and Fuzzy-PID Control in Series Active Power Filter, Proceedings of the 2007, IEEE International Conference on Mechatronics and Automation August 5 - 8, 2007, Harbin, China, pp 2958-2962.
[8] Huann-Keng Chiang, Bor-Ren Lin, “Hybrid Active Power Filter for power quality compensation” EEEE, PEDS 2005 pp. 949–954.
[9] Huann-Keng Chiang, Bor-Ren Lin, Kai-Tsang Yang and Kuan-Wei Wu, Hybrid Active Power Filter for power quality compensation, EEEE PEDS 2005, pp 950-954.
[10] V. Khadkikar, P. Aganval, A. Chandra, A.O. Bany and T.D. Nguyen, A Simple New Control Technique For Unified Power Quality Conditioner (UPQC), 2004 11th International Conference on Harmonics and Quality of Power, pp 289-293.
[11] A. Nabae, I. Takahashi, H. Akagi, A new neutral-point-clamped PWM inverter, IEEE Trans. Ind. Appl. 17 September (5), 1981, pp. 518–523.
[12] V. Aburto, M. Schneider, L. Moran, J.An. Dixon, active power filter implemented with a three-level NPC voltage-source inverter, IEEE Power Electronics Specialists Conference, Jun 1997, pp 1121 – 1126.
[13] Jin. Taotao, Wen. Jun, K. Smedley, Control and topologies for three-phase three-level active power filters, IEEE Applied Power Electronics Conference and Exposition, March 2005, pp 655 – 664.
[14] B.-R. Lin, T.-Y. Yang,, Three-level voltage-source inverter for shunt active filter, IEE, Electric Power Applications, Nov. 2004, pp 744 – 751.
[15] B.-R. Lin, H. K. Chiang, C.-H. Huang, “Three-phase three-level active power filter with a clamped capacitor topology”, IEE, Electric Power Applications, July 2006, pp. 513 – 522.
[16] H. Akagi, A. Nabae, Control strategy of active power filters using multiple voltage source PWM converters, IEEE Trans. Ind. Appl. IA-22 (May/June) 1986, pp. 460–465.
[17] Akagi, H., Kanazawa, Y., Nabae, A., 1983. Generalized theory of the instantaneous reactive power in three-phase circuits, In proceedings of the 1985 international power electronics conference, Tokyo, Japan, pp. 1375-1386.
[18] Gaiceau, M., 2005. Active power compensator of the current harmonics based on the instantaneous power theory, The annals of “dunarea de jos” University of Galati FASCLE III. ISSN 1221-454X. pp 23-28.
[19] A. Hamadi, K. El-Haddad, S. Rahmani and H. Kankan, Comparison of fuzzy logic and Proportional Integral Controller of Voltage Source Active Filter Compensating Current Harmonics and Power Factor, IEEE International Conference on Industrial Technology (ICIT), 2004. pp. 645-650.
[20] S. Saad, L. Zellouma, Fuzzy logic controller for three-level shunt active filter compensating harmonics and reactive power, Elesevier, Electric Power Systems Research 79 (2009) 1337–1341.
[21] L. Zellouma, S. Saad, Three Phase Three Level Shunt Active Filter, *2nd International Conference on Electrical and Electronics Engineering TCEEE’08*, April 21-23, 2008, Amar Telidji University Laghouat, Algeria.