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Improvement of Dynamic Behavior of Shunt Active Power Filter Using Fuzzy Instantaneous Power Theory

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Abstract

Dynamic behavior of the harmonic detection part of an active power filter (APF) has an essential role in filter compensation performances during transient conditions. Instantaneous power (*p–q*) theory is extensively used to design harmonic detectors for active filters. Large overshoot of *p–q* theory method deteriorates filter response at a large and rapid load change. In this study the harmonic estimation of an APF during transient conditions for balanced three-phase nonlinear loads is conducted. A novel fuzzy instantaneous power (FIP) theory is proposed to improve conventional *p–q* theory dynamic performances during transient conditions to adapt automatically to any random and rapid nonlinear load change. Adding fuzzy rules in *p–q* theory improves the decomposition of the alternating current components of active and reactive power signals and develops correct reference during rapid and random current variation. Modifying *p–q* theory internal high-pass filter performance using fuzzy rules without any drawback is a prospect. In the simulated system using MATLAB/SIMULINK, the shunt active filter is connected to a rapidly time-varying nonlinear load. The harmonic detection parts of the shunt active filter are developed for FIP theory-based and *p–q* theory-based algorithms. The harmonic detector hardware is also developed using the TMS320F28335 digital signal processor and connected to a laboratory nonlinear load. The software is developed for FIP theory-based and *p–q* theory-based algorithms. The simulation and experimental tests results verify the ability of the new technique in harmonic detection of rapid changing nonlinear loads.

Key words: Fuzzy instantaneous power (FIP) theory, Fuzzy logic controller, *p–q* theory, Time-varying harmonic

I. INTRODUCTION

In industrial drive systems that control high acceleration processes, the use of a line reactor to improve rapid and sharp current variation is impossible. Large values of current harmonics are injected to the alternating current (AC) line and must be filtered. An ideal active power filter (APF) must have adaptability and flexibility to any kind of load current variation. The dynamic performance of an APF highly depends on the harmonic detection part of the filter closed-loop control system. One of the most important properties of harmonic detection is tracking ability in steady-state and transient conditions. Although many different methods are proposed for harmonic detection, instantaneous power (*p–q*) theory is extensively used for this purpose [1]-[13]. Recently, some methods have been applied to improve the dynamic behavior of harmonic estimation.

The frequency-based and neural-based methods have several drawbacks. For example, the frequency-based methods are time consuming, require large computational effort, and experience initial adaptation delay, and the neural-based methods requires initial training and have poor response in untrained conditions during harmonic detection application [14]-[23]. The ability to control the APFs in real time, the simplicity of the calculations, and the flexibility to apply to three-phase systems with or without neutral wire are the main reasons for the extensive use of the *p–q* method. *p–q* theory needs an additional phase-locked loop (PLL) circuit for synchronization. Therefore, the *p–q* method is frequency variant [24]-[26]. However, some problems occur because of misinterpretations of this theory. One of the main drawbacks of *p–q* theory method is its large overshoot. *p–q* theory method does not respond well in large and rapid load change

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systems, such as high-power speed drives [3], [9], [10], [13]. A combination of AC and direct current (DC) signals and invisible signals with intermediate frequency less than the main harmonic tend to deteriorate the method performance during transient conditions. Compromising between cutting frequencies of the high-pass filter (HPF) and filter order do not lead to successful solutions. Increasing phase error and deterioration of output quality are the result of this compromise. Fuzzy logic is an alternative approach to handle this type of problem [17]-[23]. However, many issues on fuzzy logic application in different parts of the APF exist. Harmonic detector, current controller, and DC bus voltage controller are improved with fuzzy-based configuration [19]. Fuzzy logic-based shunt APF shows better dynamic response and higher control precision compared with other filters [21]. Modifying filter performances using fuzzy rules without any drawback is a prospect. In this study, fuzzy instantaneous power (FIP) theory is introduced. First, *p–q* theory will be reviewed, and then FIP theory will be explained in Section 2. In Sections 3 and 4, the application of *p–q* theory and FIP theory in harmonic detection with rapid load change is simulated and implemented using digital signal processor (DSP), and the results are discussed.

II. Harmonic Detection Methods and Problem

Different algorithms are used for harmonic detection, and most debates focus on detection accuracy, speed, filter stability, and easy and inexpensive implementation. In a rapidly time-varying condition, the most important property of a harmonic detector is the speed of the algorithm [3]-[6], [9]. Based on classification relative to the domain where the mathematical model is developed, the two major directions are the time-domain and frequency-domain methods. The time-domain methods are mainly used to gain more speed or fewer calculations compared with the frequency-domain methods. Furthermore, in time-domain methods, the three important dynamic specifications of detection algorithms, that is, phase error, settling time, and overshoot of *p–q* theory method, are better than other methods [9], [13].

A. Instantaneous Power (p–q) Theory

p–q theory determines the harmonic distortion from the instantaneous power calculation in a three-phase system, which is the multiplication of the instantaneous values of the currents and voltages [9]. The calculations may be conducted in the α–β coordinates, as shown in Eq. (1), for three balanced sinusoidal voltage supplies and a balanced load:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}. \tag{1}$$

The values of the instantaneous powers p and q, which are the real and imaginary powers, respectively, contain DC and AC components depending on the existing active, reactive, and distorted powers in the system. The values of p and q can be expressed based on Eq. (1) in terms of the DC components plus the AC components, as follows:

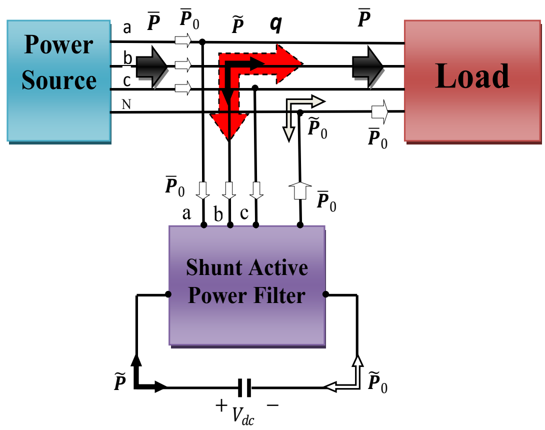


Fig. 1. Compensation of power components p, q, and p_0 in α–β–0 coordinates.

$$p = \bar{p} + \tilde{p} \tag{2}$$

$$q = \bar{q} + \tilde{q} \tag{3}$$

where $\bar{p}$ is the DC component of the instantaneous power p and is related to the conventional fundamental active current; $\tilde{p}$ is the AC component of the instantaneous power p and is related to the harmonic currents; $\bar{q}$ is the DC component of the imaginary instantaneous power q and is related to the reactive power generated by the fundamental components of voltages and currents; and $\tilde{q}$ is the AC component of the instantaneous imaginary power q and is related to the harmonic currents.

The zero sequence power exists only in three-phase systems with neutral wire. Furthermore, the systems must have unbalanced voltages and currents and/or third harmonics in the voltage and current of at least one phase.

$$p_0 = \bar{p}_0 + \tilde{p}_0, \tag{4}$$

where $\bar{p}_0$ is the DC component of the instantaneous zero sequence power and corresponds to the energy per time unity, which is transferred from the power supply to the load through the zero sequence components of voltage and current and $\tilde{p}_0$ is the AC component of the instantaneous zero sequence power and corresponds to the energy per time unity that is exchanged between the power supply and the load through the zero sequence components. A shunt APF, as shown in Fig. 1, can theoretically compensate for the AC component of the active power and also the DC and AC components of the reactive and zero sequence power.

To compensate for current harmonics generated by nonlinear loads, the reference signal of the shunt APF must include the values of $\tilde{p}$ and $\tilde{q}$. In this case, the reference

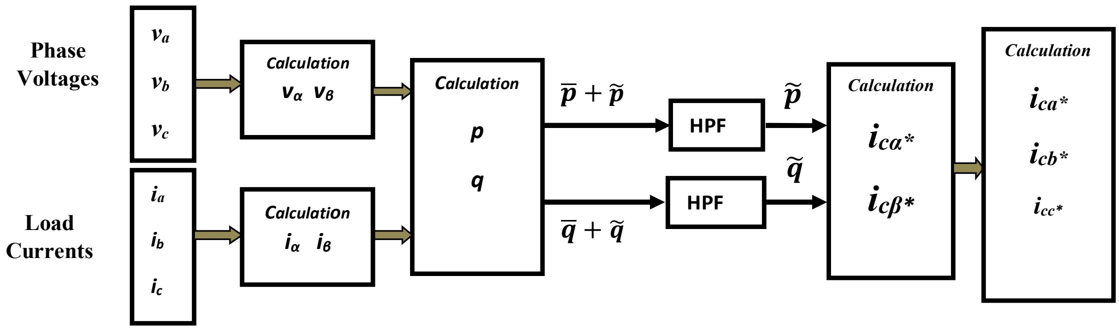


Fig. 2. Principle flow diagram of *p–q* theory for the calculation of reference currents in the balanced condition.

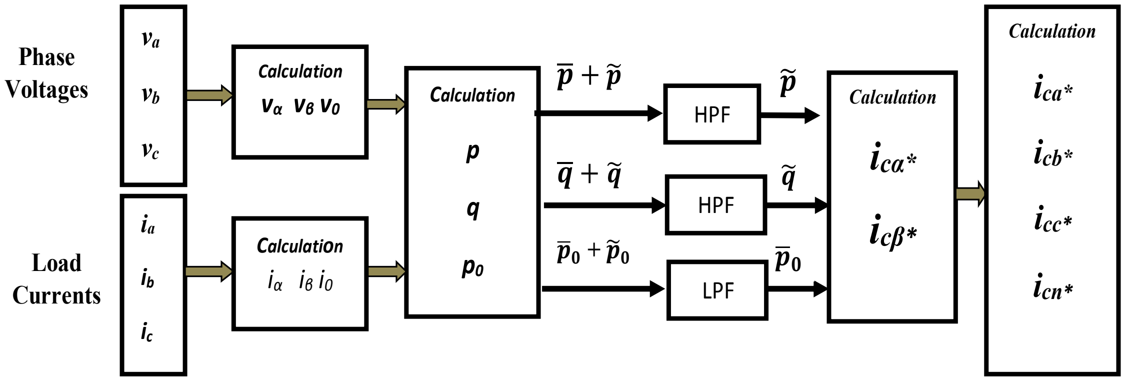


Fig. 3. Flow diagram of *p–q* theory for the calculation of reference currents in the unbalanced three-phase four-wire system.

currents required by the APF are calculated from the following expression for a balanced system:

$$\begin{bmatrix} i_{c\alpha*} \\ i_{c\beta*} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix}, \tag{5}$$

$$\begin{bmatrix} i_{ca*} \\ i_{cb*} \\ i_{cc*} \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} i_{c\alpha*} \\ i_{c\beta*} \end{bmatrix}. \tag{6}$$

Fig. 2 shows the principle diagram of *p–q* theory for determining the compensated reference currents in the balanced condition. The DC components of *p* and *q* represent the active and reactive powers and must be removed by HPF (with a cutting frequency between 5 and 35 Hz) to retain only the AC signals for harmonic current compensation. The AC components are transferred to the abc frame and represent the harmonic distortion, which are considered references for the current controller. The HPF is usually a digital filter. The numerical implementation of the HPF influences the dynamics and accuracy of the entire APF [12].

When the three-phase system is unbalanced, the reference currents of the APF, as shown in Fig. 1, are determined as follows:

$$\begin{bmatrix} i_{c\alpha*} \\ i_{c\beta*} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} - \bar{p}_0 \\ \tilde{q} \end{bmatrix}. \tag{7}$$

Given that the zero sequence current must be compensated, the reference compensation current in the 0 coordinate is i_0 itself:

$$i_{c0*} = i_0, \tag{8}$$

$$\begin{bmatrix} i_{ca*} \\ i_{cb*} \\ i_{cc*} \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} i_{c0*} \\ i_{c\alpha*} \\ i_{c\beta*} \end{bmatrix}, \tag{9}$$

$$i_{cn*} = -\left(i_{ca*} + i_{cb*} + i_{cc*}\right). \tag{10}$$

B. Some Problems of p–q Theory

The implementation of *p–q* theory encounters some problems in real application. The two main problems are large overshoot and dependence on voltage shape. In harmonic detection based on *p–q* theory with rapid load change, the AC components of *p* and *q* contain erroneous terms because of the rapid change of harmonic current amplitude and phase and the nondeterministic relationship between them. In some industrial systems such as DC drives during transient conditions, the phase angle of the drive current changes rapidly. By this variation, not only the harmonic current varies but also the reactive power changes considerably. Large variation of reactive power in rapid transient conditions cannot be distinguished from harmonic

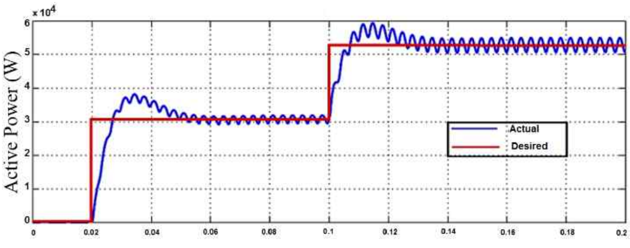


Fig. 4. Desired and actual variation of $\overline{p}$.

variation based on *p–q* theory and results in high overshoot in detection response [13]. The HPF filtering capability has an essential role in the quality and accuracy of the detected harmonics. Increasing the filter order or decreasing the cutting frequency increases the phase error and degrades the overshoot. In the rapidly time-varying condition, the DC component of *p* and *q* may vary with a frequency less than the main harmonic frequency (intermediate frequency). To consider these phenomena, Eqs. (2) and (3) can be rewritten as follows:

$$p = \overline{p} + \Delta p + \tilde{p}, \tag{11}$$

$$q = \overline{q} + \Delta q + \tilde{q}. \tag{12}$$

$\overline{p}$ and $\overline{q}$ in rapid load change can have step reference changes (as shown in Fig. 4 for the desired active power). However, the actual active power has variations because of the system dynamics, as shown in Fig. 4. The difference between the actual value of $\overline{p}$ and its estimated value (which is equal to its desired value) is called Δp. The terms Δp and Δq correspond to the “slow” variation of the DC component of *p* and *q* and are not related to harmonics. However, these components become related to harmonics when they pass through the HPF, thus increasing the values of the AC components of *p* and *q* and producing undesired responses.

The current reference calculations of Eqs. (1) to (5) are also affected by zero sequence components because of an existing unbalanced system. Therefore, an Δp_0 component must be added to provide a complete analysis of the unbalanced systems [10]:

$$p_0 = \overline{p}_0 + \Delta p_0 + \tilde{p}_0. \tag{13}$$

C. FIP Theory

When a system is too complex or too poorly understood to be described in precise mathematical terms, fuzzy modeling provides the ability to linguistically specify approximate relationships between the inputs and desired outputs. The relationships are represented by a set of fuzzy if–then rules in which the antecedent is an approximate representation of the state of the system and the consequent provides a range of potential responses [18]-[23]. With the use of the fuzzy algorithm, decision making can be easy when the subject is

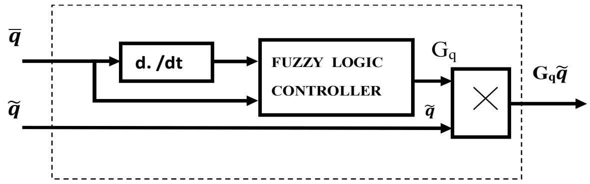


Fig. 5. Principle diagram of the simplified fuzzy modifier for *q*.

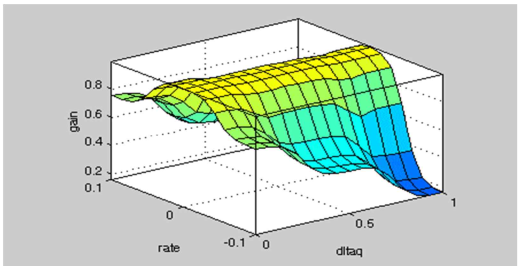


Fig. 6. Fuzzy controller surface viewer.

TABLE I
FUZZY INTERFACE RULE

Δq/rate	None	Positive	Negative
Low	Normal	High	High
Mid	Normal	Medium	Medium
High	Normal	Low	Low

the outcome of two or more parameter relationships and interactions. Improving the filtering capability without changing the cutoff frequency or filter order is a new approach to achieve a reasonable response with rapid load change. The use of Eq. (7) to calculate the reference current with $\tilde{p}$, $\tilde{q}$, and $\overline{p}_0$ during transition leads to high overshoot in the output. Attenuating these signals is a simple approach to correct the overshoot problem during rapid load change. The attenuator coefficients are determined by using the fuzzy modifier. The fuzzy modifier contains three fuzzy controllers with two inputs and one output. Fig. 5 shows the principle diagram of the simplified fuzzy modifier for the *q* variable, where G_q is the fuzzy modifier coefficient and $0.1 < G_q \leq 1$.

The fuzzy logic controller (FLC) based on the signal value and its rate of change determines the modifier coefficient, and its inference rules with nine rules are shown in Table I.

The performance of any FLC can be improved by increasing the number of rules present in the rule base of the controller, but with increased computation cost. The required computational time slows down the process considerably [22]. Some studies regarding the reduction of the rule base number have been reported. Some issues on the design and rule base size reduction for the fuzzy control exist, and some concepts regarding resizing of the rule base by removing inconsistent and redundant rules have been proposed [19], [20]. Many studies have proposed the 49-rule FLC for the control of the shunt APF. The 49-rule FLC has the drawback of a large

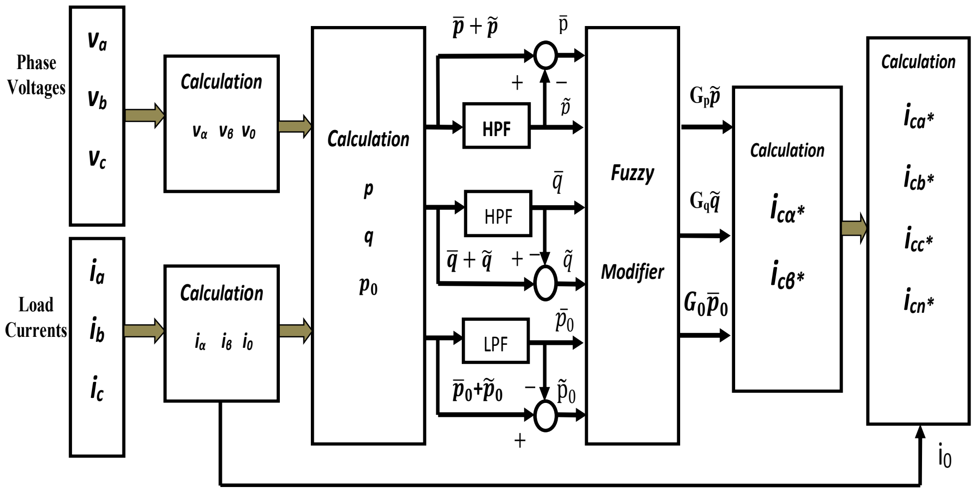


Fig. 7. Principle flow diagram of FIP theory (unbalanced four-wire system).

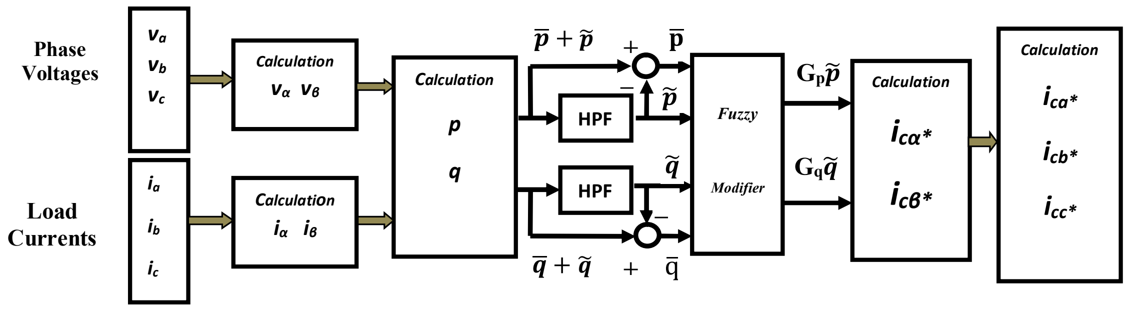


Fig. 8. Principle flow diagram of FIP theory (for balanced systems).

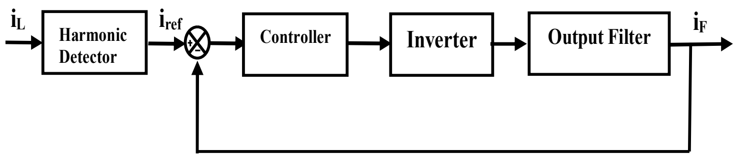


Fig. 9. Block diagram of the shunt APF.

number of fuzzy sets and control rules. This drawback is overcome by approximation using the simpler nine-rule FLC [20], [22] and the simplest four-rule FLC [19]. In this application with a compromise between transient and steady-state behaviors of the APF, a nine-rule FLC is selected. The behavior of the control surface, which relates the input and output variables of the system, is governed by a set of rules. When a set of input variables are read, each rule that has any degree of truth in its premise is fired and contributes to the formation of the control surface by approximately modifying it. When all rules are fired, the resulting control surface is expressed as a fuzzy set to represent the output. Fig. 6 shows the fuzzy controller surface viewer, which graphically defines the fuzzy inference rules. Using FIP theory-based harmonic detector, the principle flow diagram shown in Fig. 3 can be modified, as shown in Fig. 7.

In this case, Eq. (7) can be rewritten as follows:

$$\begin{bmatrix} i_{c\alpha*} \\ i_{c\beta*} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} G_p \cdot \tilde{p} - G_{p0} \cdot \bar{p}_0 \\ G_q \cdot \tilde{q} \end{bmatrix}. \quad (14)$$

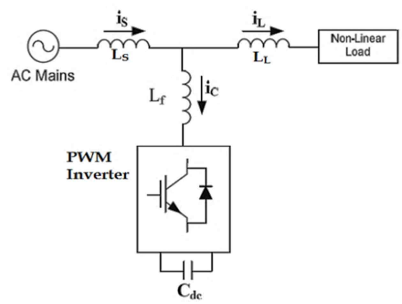


Fig. 10. Shunt APF.

For a balanced three-phase system, p_0 is not considered. Expanding this method to balanced three-phase systems modifies Eqs. (14) and (15) and Figs. 7 and 8.

$$\begin{bmatrix} i_{c\alpha*} \\ i_{c\beta*} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} G_p \cdot \tilde{p} \\ G_q \cdot \tilde{q} \end{bmatrix}. \quad (15)$$

D. Effect of the New Harmonic Detection Method on the Stability of the Current Control System

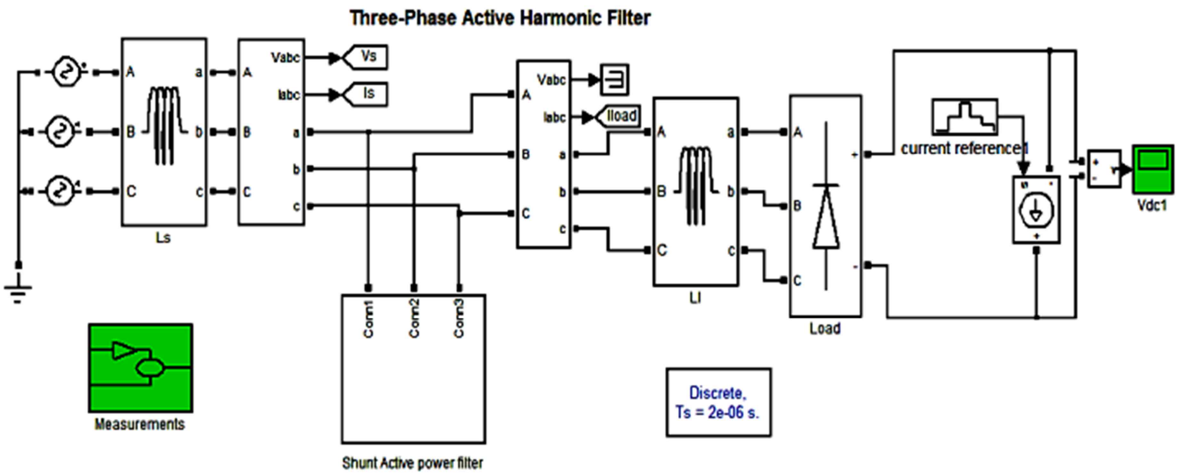
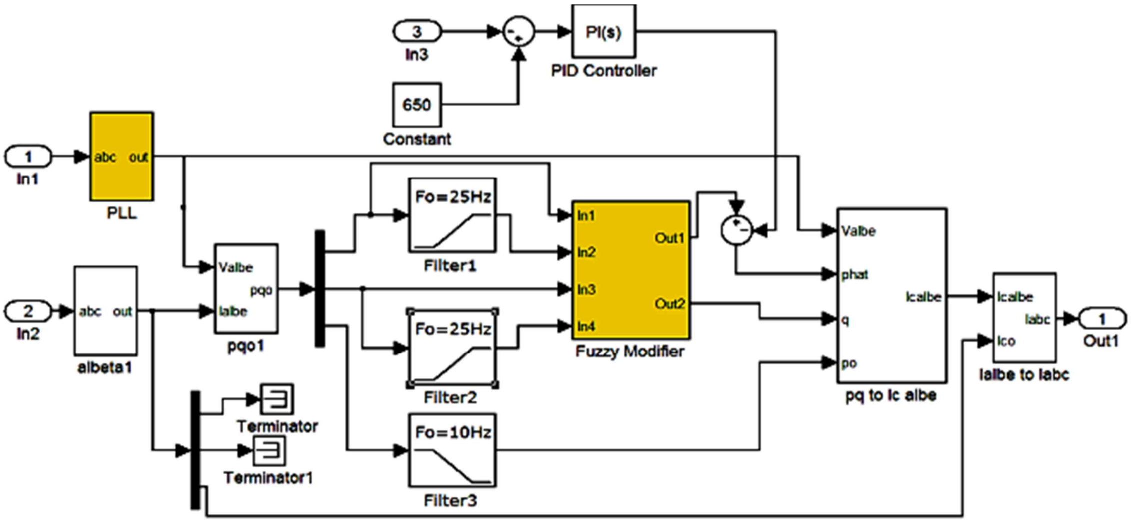
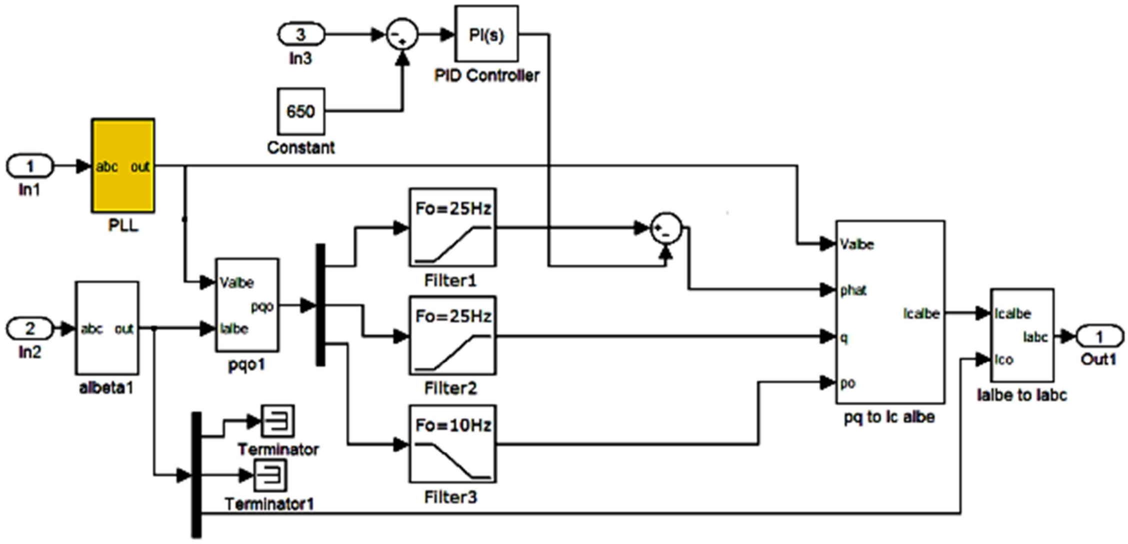


Fig. 11. SIMULINK model of the programmable nonlinear load with shunt APF.

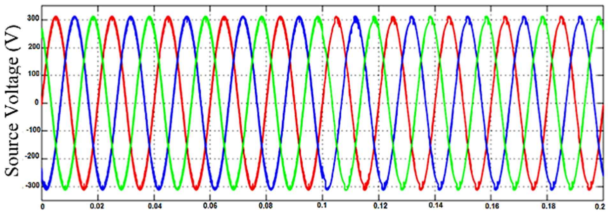


(a)



(b)

Fig. 12. (a) FIP theory-based reference current generator. (b) *p–q* theory-based reference current generator.



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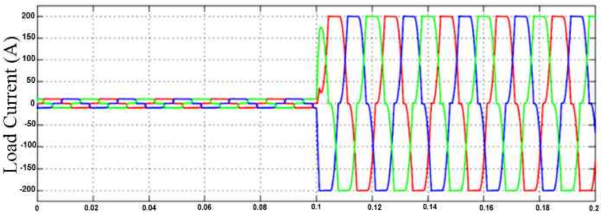

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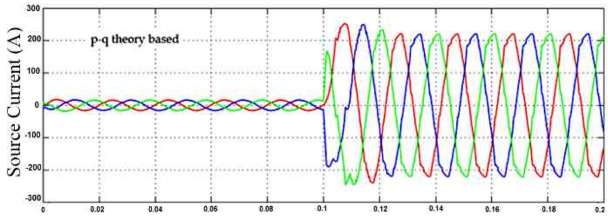

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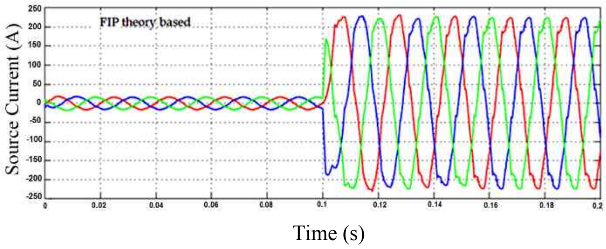
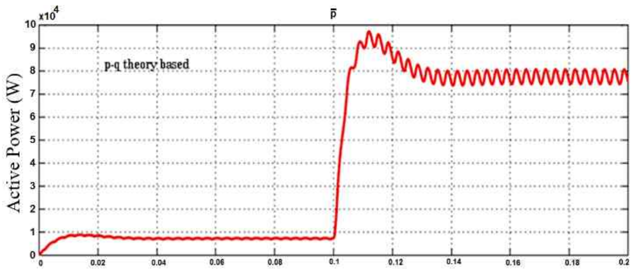


(d)

Fig. 13. Simulated system signals for *p–q* and FIP theory-based APF compensation. (a) Source voltage. (b) Load current. (c) *p–q* theory-based compensated source current. (d) FIP theory-based compensated source current.



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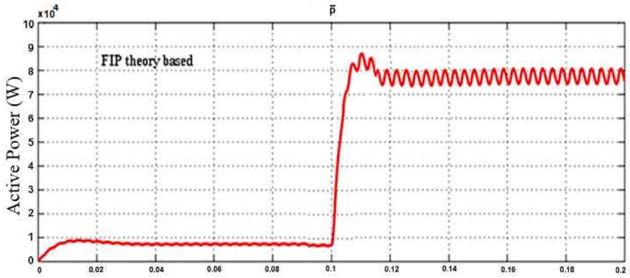

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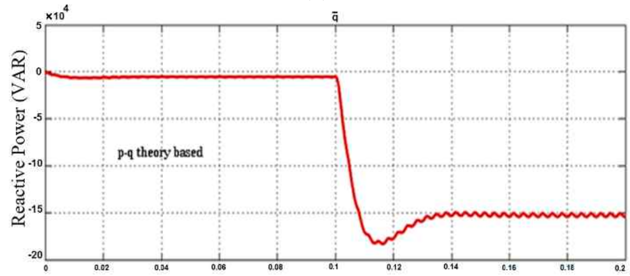

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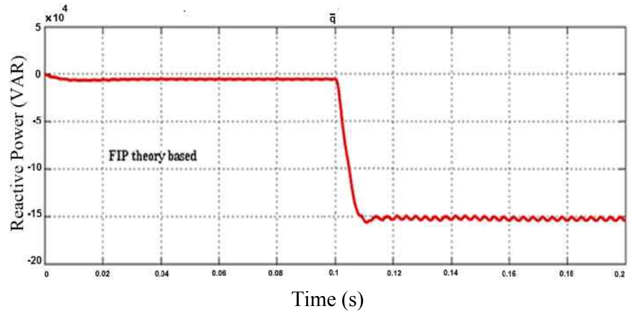


(d)

Fig. 14. Simulated system signals for *p–q* and FIP theory-based current reference generator. (a) *p–q* theory-based estimated $\overline{p}$. (b) FIP theory-based estimated $\overline{p}$. (c) *p–q* theory-based estimated $\overline{q}$. (d) FIP theory-based estimated $\overline{q}$.

In the new method, the cutoff frequencies and order of HPFs and low-pass filters are unchanged. Only the amplitude of the filter output signal is adaptively varied. Therefore, no differences in the phase of the filtered signals in the two methods were observed. Fig. 9 shows the block diagram of the shunt APF control system. The dynamic performance of the harmonic detector has no effect on the characteristic equation and stability of the closed-loop control system because it is out of the control loop, which sets the control system reference signal value. The performance of this block fixes the overall harmonic compensation quality. As such, hardware generation using the two harmonic detection methods can be conducted individually, and the active filter can be omitted [13].

III. Simulation of the Nonlinear Load with Active Power Filter and the Results

In this paper, harmonic cancelation is conducted using a pure shunt type APF as Fig. 10. A voltage source pulse-width modulation inverter, with insulated gate bipolar transistor switches, series inductor (L_F), and energy storage capacitor (C_{dc}) on the DC bus, is used as a shunt active filter.

Fig. 11 shows the simulation of the programmable nonlinear load. The load is a three-phase bridge-controlled rectifier with programmable current source, which is the same as the three-phase AC voltage controller of the preheat section in a galvanization process that works in the phase angle control mode with rapid current changing capability. In

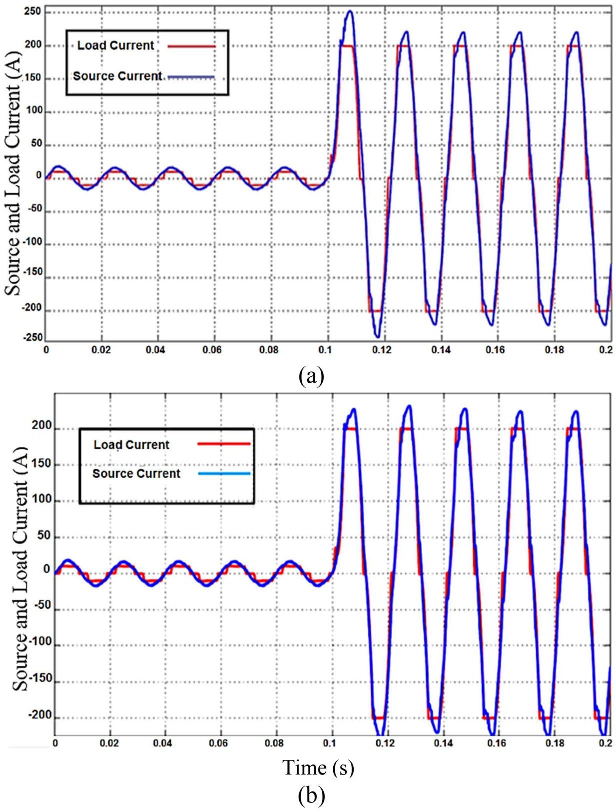


Fig. 15. Step change of the load and source current of phase "b" in (a) *p–q* theory-based compensation method and (b) FIP theory-based compensation method.

this model, a PLL-based voltage reference generator and a hysteresis-based controller for current control are used [5]. Fig. 12 shows the SIMULINK model of *p–q* and FIP theory-based reference current generator, with the fuzzy modifier as their only difference.

A. Comparison of p–q Theory-Based and FIP Theory-Based Compensation Methods in Rapid Load Change

The load current is changed from 20 A to 200 A as a step function at time 0.1 s, as shown in Fig. 13. The simulated source voltage and load current are shown in Figs. 13(a) and 13(b), respectively. Figs. 13(c) and 13(d) show the source currents that are compensated by the *p–q* and FIP methods, respectively.

As shown in Figs. 14(a) and 14(b), the DC part of the estimated active power in *p–q* theory-based and FIP theory-based methods has 23% and 5% overshoot, respectively. Figs. 14(b) and 14(c) show that the DC part of *q* in the two methods has 20% and 3% overshoot, respectively. The higher overshoot in the *p–q* reference current estimation method results in a higher overshoot in the compensated current. The unwanted part of variation can be omitted by the fuzzy modifier.

For more details, Fig. 15 shows one phase current and compares *p–q* and FIP theory-based dynamic performances.

TABLE II

P–Q THEORY-BASED AND FIP THEORY-BASED DYNAMIC PERFORMANCE

	p–q	FIP
Overshoot (%)	13.20	<1
Settling time (ms)	75	5
Phase error (°)	<5	<2

TABLE III

THD OF THE LOAD AND SOURCE CURRENT IN STEADY STATE

	Load DC	$THD_{p\text{–}q}$	THD_{FIP}
Load Current: i_L	200 A	23.20%	23.20%
Source Current: i_S	200 A	4.65%	4.70%
Load Current: i_L	20 A	28.67%	28.67%
Source Current: i_S	20 A	3.54%	3.71%

As shown in Table III, the FIP theory-based compensation method with nine rules has similarity to the *p–q* theory-based method in steady state. The total harmonic distortion (THD) of the supply current in both methods is below the 5% limit imposed by the IEEE 519 standard, where the THD of the load current is 23.2% at 200 A and 28.67% at 20 A.With an increase in the number of rules of the FLC, the THD of the source current in the FIP theory-based method decreases to a value similar to that of the THD of the *p–q* theory-based method. However, the computational time increases, which slows down the process considerably. The nine-rule FLC satisfies the acceptable transient and steady-state condition performances.

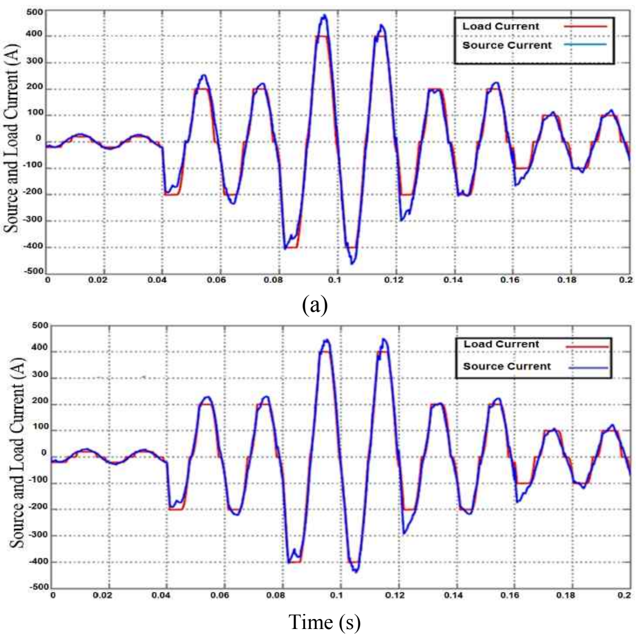
B. Comparison of p–q Theory-Based and FIP Theory-Based Nonlinear Balance Load with Rapid Change

In some applications, load current has random variation. For instance, high-power traction DC drives in four quadrant operation have rapid and random load current variation during direction-changing rotation. The results of rapid current reference are [20 200 400 200 100], as shown in Fig. 15. The FIP theory-based method is more stable and more adaptable to rapid current change.

C. Comparison of p–q Theory-Based and FIP Theory-Based Compensation Behavior during Transient Load Change

In the simulated system, nonlinear load (three-phase rectifier with constant current source) is replaced with nonlinear load (three-phase rectifier with resistive capacitive load) with transient behavior, as shown in Fig. 17.

After closing the breaker at $t = 0.1$ s, the load current varies from 50 A to 100 A as a step function with transient behavior. The load current has a settling time of 100 ms and increases up to 268 A in transient conditions. The compensated source current using the *p–q* theory-based method[Fig. 18(a)] has a



(a)

(b)

Fig. 16. Rapid change of load and source current of phase “b” in (a) *p–q* theory-based compensation and (b) FIP theory-based compensation.

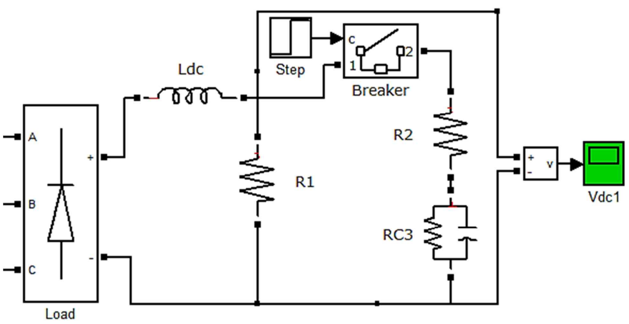


Fig. 17. SIMULINK model of nonlinear load with transient behavior.

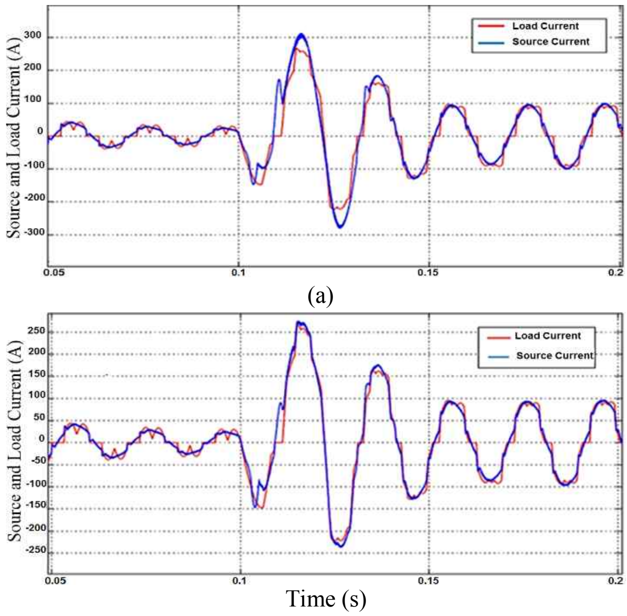
peak value of 305 A. For the FIP theory-based compensated source current [Fig. 18(b)], the peak value is 271 A. At the steady-state condition, no differences were observed.

IV. Experimental Setup and Results

A laboratory-controlled rectifier DC drive with a 3 hp DC motor coupled with a 2.2 kW AC generator used as nonlinear load. The harmonic detection methods were implemented using TMS320F28335 DSP. Hardware-in-the-loop simulation with a serial communications interface is a utility of this family of processors for many tasks such as online data logging in SIMULINK environments using Texas Instrument Code Composer Studio [27]. Fig. 19 shows the experimental setup.

To evaluate the accuracy and dynamic behavior of the two methods, the harmonic component of the load current is removed, which results in the “expected” source current. This signal resembles the reference current for source current compensation. The dynamic performance of this current is the same as the closed-loop source current. In investigating the effectiveness of the two methods during rapid load change, the breaker is closed and the AC generator is loaded with a resistive load. The rectifier effective current varies from 0.4 A to 1.5 A as a step function. The expected compensated source current using *p–q* theory has a peak value of 2.65 A [Fig. 20(a)]. For the FIP theory-based expected compensated source current, the peak value is 2.2 A [Fig. 20(b)]. During transient conditions, no differences were observed. and the peak value is 2.15 A. The overshoot of the first method is 23.2% and that of the second method is 2.3%. This result shows that the second method performs better during transient conditions.

The simulation and experimental results show that the FIP theory-based method is more stable than the conventional *p–q*



(a)

(b)

Fig. 18. Transient behavior of the load and source current of phase “b” in (a) *p–q* theory-based and (b) FIP theory-based compensation methods.

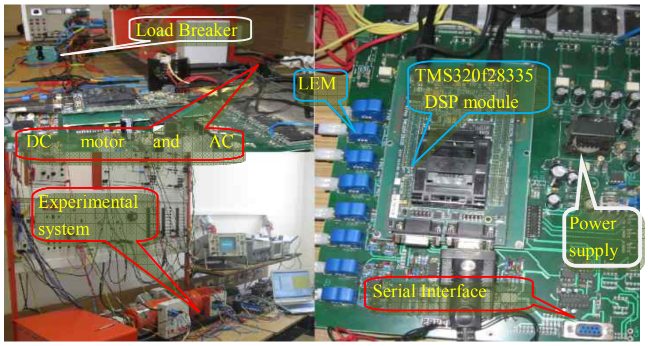


Fig. 19. Experimental system setup.

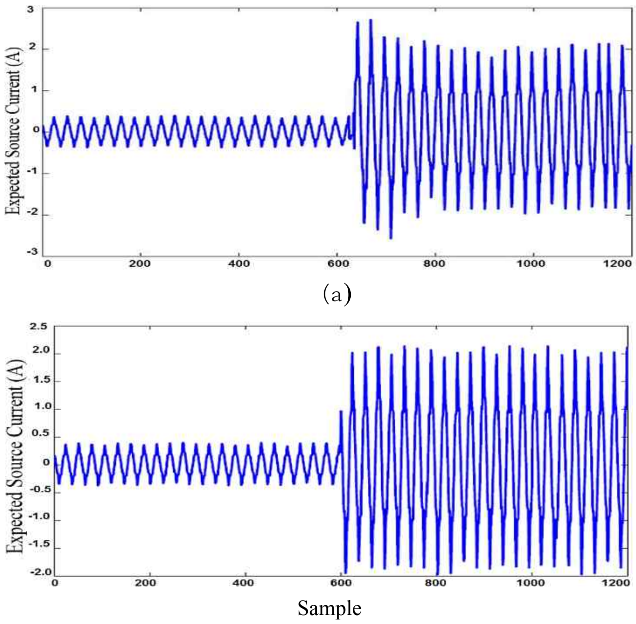


Fig. 20. (a) *p–q* theory-based and (b) FIP theory-based compensation behavior in step change of the load current.

theory-based method. In addition, the FIP theory-based method has a fast, reliable, and good tracking ability.

V. CONCLUSIONS

FIP theory combines *p–q* theory and fuzzy logic techniques to efficiently compensate for the source current in transient conditions. This configuration improves the dynamic behavior of the harmonic detector without any drawback. Through correct selection of the fuzzy modifier (number of rules of the FLC), the response has low overshoot for any condition and the tracking ability of the harmonic detector improves. Moreover, other behaviors and performances, such as settling time and stability of the generated compensated reference currents, are enhanced. Compared with other methods, the FIP theory-based method has a unique behavior in random current and harmonic variation conditions. The FIP theory-based method has a precise compensation capability and is computationally efficient for real-time implementation. The results of the simulation and experimental tests show the ability of the new technique in dynamic harmonic detection.

REFERENCES

[1] H. Akagi, Y. Kanazawa, and A. Nabae "Generalized theory of the instantaneous reactive power in three-phase circuits," *IPEC'83 Int. Power Electronics Conf.*, pp. 1375-1386, 1983.

[2] H. Akagi, Y. Kanazawa, and A. Nabae "Instantaneous reactive power compensator comprising switching devices without energy storage components," *IEEE Trans. Ind. Appl.* Vol. 20, No. 3, pp. 625-630, May/Jun. 1984.

[3] N. S. Rao and H. J. Jayatheertha, "Modeling and simulation of various SRF methods for shunt active power filter and application to BLDC drive," *International Journal of Advanced Engineering Research and Studies,* Vol. 1, No. 4, pp. 18-22, Jul.-Sep. 2012.

[4] E. Latha Mercy, R. Karthick, S. Arumugam "A comparative performance analysis of four control algorithms for a three phase shunt active power filter," *International Journal of Computer Science and Network Security,* Vol. 10, No. 6, pp. 1-7, Jun. 2010.

[5] L. Honda and K. Cao "Active power filter simulation based on instantaneous reactive power theory and the PWM hysteresis control mode," *IEEE 10th International Conference on Electronic Measurement & Instruments*, Vol. 4, pp. 95-100, 2011.

[6] J. Afonso, C. Couto, and J. Martins, "Active filters with control based on the p-q theory," *IEEE Industrial Electronics Society Newsletter,* Vol. 47, No. 3, pp. 5-10, Sep. 2000.

[7] E. H. Watanabe, R. M. Stephan, and M. Aredes, "New concepts of instantaneous active and reactive powers in electrical systems with generic loads," *IEEE Trans. Power Del.,* Vol. 8, No. 2, pp. 697-703, Apr. 1993.

[8] L. S. Czarnecki "Instantaneous reactive power p-q theory and power properties of three-phase systems," *IEEE Trans. Power Del.*, Vol. 21, No. 1, pp. 362-367, Jan. 2006.

[9] R. Sriranjani and S. Jayalalitha "Comparison of passive active and hybrid filter in front-end system," *International Journal of Communication Engineering Applications-IJCEA,* Vol. 3, No. 3, pp. 503-506, Jul. 2012.

[10] S. Garlapati and R. Gupta, "Shunt active power filter as front end converter for DC loads," *2012 IEEE 5th India International Conference on Power Electronics (IICPE),* pp. 1-6, 2012.

[11] A. Bitoleanu, M. Popescu, and V. Suru, "P–q power theory: Some theoretical and practical aspects," *2010 IEEE International School on Non sinusoidal Currents and Compensation (ISNCC),* pp. 74-79, 2010.

[12] M. I. M. Montero, E. R. Cadaval, and F. B. González, "Comparison of control strategies for shunt active power filters in three-phase four-wire systems," *IEEE Trans. Power Electron.,* Vol. 22, No. 1, pp. 229-236, Jan. 2007.

[13] L. Asiminoaei, S. Hansen, and F. Blaabjerg, "Evaluation of harmonic detection methods for active power filter applications," *Applied Power Electronics Conference and Exposition, 2005. APEC 2005. Twentieth Annual IEEE,* Vol. 1, pp. 635-641, 2005.

[14] D. Gowtami, S. Ravindra, A. Mallikarjunapasad, and G Kishore, "A novel MATLAB model of ANN based controllers to improve the dynamic performance of a shunt active power filter," *International Journal of Electrical and Electronics Engineering* (IJEEE) Vol. 2, Iss-2,3,4, pp. 109-114, 2012.

[15] P. Wira, D. Ould Abdeslam, and J. Mercklé, "Learning and adaptive algorithms for compensating for harmonic distortions: A comparative studym" *International Conference on Electrical Engineering and its Applications (ICEE 2008) Sidi Bel-Abbes, Algeria,* 2008.

[16] S. Janpong, K.-L.Areerak, and K.-N. Areerak "A literature survey of neural network applications for shunt active power filters," World Academy of Science, Engineering and Technology, Vol. 5, No. 12, pp. 273-279, 2011.

[17] G. S. Nhivekar, S. S. Nirmale, R. R. Mudholker "Implementation of fuzzy logic control algorithm in embedded microcomputers for dedicated application,"

International Journal of Engineering, Science and Technology, Vol. 3, No. 4, pp. 276-283, 2011.

[18] Z. A. Memon, M. A. Uqaili, M. A. Unar, "Estimation of compensation current reference using fuzzy logic controller for three-phase hybrid active power filter," *International Journal of Computer Applications*, Vol. 43, No. 11, pp. 16-21, Apr. 2012.

[19] R. Singh, A. K. Singh, and R. K. Arya "Approximated fuzzy logic controlled shunt active power filter for improved power quality," *Expert Systems,* Vol. 30, No. 2, pp. 152-161, May 2013.

[20] S. Bangia, P. R. Sharma, and M. Garg "A novel control strategy for enhancement of power quality using fuzzy logic," *International Journal of Instrumentation and Control Systems (IJICS)*, Vol. 2, No. 4, pp. 51-59, Oct. 2012.

[21] Y. H. Kim, S. C. Ahn, and W. H. Kwon, "Computational complexity of general fuzzy logic control and its simplification for a loop controller," *Fuzzy Sets and Systems*, Vol. 111, No. 2, pp. 215-224, Apr. 2000.

[22] A. Azam and M. H. Khan "Reduced rule fuzzy logic controller for performance improvement of process control," in *Proc. 2013 IEEE Conference on Information and Communication Technologies (ICT 2013)*, pp. 894-898, 2013.

[23] G. K. Singh, A. K. Singh, and R. Mitra, "A simple fuzzy logic based robust active power filter for harmonics minimization under random load variation," *Electric Power Systems Research*, Vol. 77, No. 8, pp. 1101-1111, Jun. 2007.

[24] E. H. Watanabe, M. Aredes, and H. Akagi, "The p-q theory for active filter control: some problems and solutions," *Revista Controle & Automação*, Vol. 15, No. 1, pp. 79-84, Jan.-Mar. 2004.

[25] L. S. Czarnecki, "Effect of supply voltage asymmetry on IRP p-q based switching compensator control," *IET Power Electron.,* Vol. 3, No. 1, pp. 11-17, Jan. 2010.

[26] M. Yavari, M. Sabahi, and E. Babaei, "Enhancement of instantaneous power theory under unbalanced grid voltages condition using positive sinusoidal signal regulator," *2012 IEEE 5th India International Conference on Power Electronics (IICPE),* pp. 1-6, 2012.

[27] Texas Instruments, *Code Composer Studio Development Tools v3.1 Getting Started Guide,* May 2005.

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