Research Article

A Harmonics Suppression Technique in Neutral Conductor for Three-Phase-Four-Wire Distribution Systems

Satitpol khuttiyaboot and Nopbhorn Leeprechanon*
Department of Electrical and Computer Engineering,
Thammasat University, Rangsit Campus,
Khlong Nueng, Khlong Luang, Pathum Thani, 12120 Thailand

Abstract

This paper presents a harmonic mitigation technique in a neutral conductor for a three-phase-four-wires power distribution system in industries using an active filter connected in series with the neutral conductor. The controller has a combination between analogue and digital microprocessor. A connection hard switch IGBT inverter operates in pulse width modulation (PWM) mode. The proposed system is capable of mitigating odd components of harmonic currents particularly for the 3rd, 5th, 7th and 9th harmonic current produced by these loads which tends to accumulate in the neutral conductor due to its zero sequence nature, thus resulting in overloading of the neutral conductor and the distribution transformer. The existing harmonic mitigation schemes focus on re-directing zero sequence current harmonic back to the three-phase conductors. Although such schemes could prevent overloading of the distribution transformer, the neutral conductor is still burdened by the excessive current of the 3rd harmonic. The inverter therefore plays a key role in suppressing harmonic current in the neutral conductor to prevent overloading. The active filter operation will not affect the fundamental component due to the unbalanced loading, in which the neutral conductor is sized. Experimental results show that the proposed scheme can eliminate current harmonics overloading in both the neutral conductor and the distribution transformer with only a single active filter installation.

Keywords: Harmonics mitigation; neutral conductor; active filter; 4P4W.

1. Introduction

Advanced technology plays a significant role in which a large number of computers and power electronics devices in industries are connected to three-phase four-wire distribution systems. These types of load have been widely employed to deliver electric power to single-phase or three-phase loads in factories, industries and large commercial sectors. The neutral conductor usually carries the zero sequence current due to the unbalanced loading among phase conductors. As more electronic equipment such as computers, copy machines and adjustable speed drives are used in the industry; the harmonic currents drawn by their rectifier front ends also become significant. It is envisaged that the zero sequence triple (3rd , 9th ,.. 15th , …) harmonics accumulate in the neutral conductor, thus resulting in overloading of the neutral conductor and the distribution transformer. Survey results across computer sites in the U.S. indicate that 22.6% of the sites have neutral currents exceeding the full-load phase currents [2]. Inductive

---

***Correspondence** : nopbhorn@engr.tu.ac.th

ballasts inject considerable harmonics in neutral conductors; fire incident has been reported due to such overloading [4]. Transformer arrangement [5], active filter systems based on power electronics components [6], [7], [8], [9], and combinations of both [10] and [11] have been used to prevent these incidences. The Instantaneous Reactive Power theory [12], [13] has been adopted to calculate the harmonics compensation command for some of the aforementioned schemes. Albeit their different circuit topologies, the above schemes use the active filter systems to provide a path between phase conductors and the neutral conductor, so the zero sequence current can circulate from the loads to the active filter systems via the neutral conductor and then back to the phase conductors. This approach eliminates the undesired current component in the portion of the neutral conductor that lies between the active filter system and the distribution transformer. But the rest of the neutral conductor still carries the excessive current harmonics, thus the danger of overloading still exists. In this paper, a harmonic mitigation technique in a neutral conductor of three-phase four-wire distribution systems is proposed. The proposed system employs an active filter inverter connected in series with the neutral conductor to mitigate the zero sequence current harmonics of the neutral conductor. The proposed system can alleviate the overloading problems on both the neutral conductor and the distribution transformer by using only one series active filter. This is a significant advantage over other schemes which may require multiple installations to cover the entire neutral conductor. Series active filter systems have been successfully applied to three-phase nonlinear loads to meet the requirement of the IEEE 519 -1992, GR /4-221 harmonic standard [14],[15],[16].

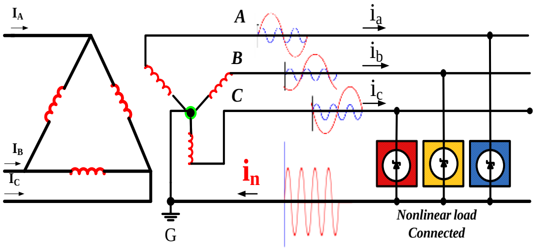


Fig.1. The proposed power system for a three-phase-four-wire distribution.

Fig.1 shows the 3rd harmonic component in neutral conductor generated by the power system. The magnitude of the 3 rd order harmonics in neutral conductor is very high before the compensation of series active filter. This occurs before using an active filter and can be expressed in (1). After adopting active filter, we can expressed the 3rd harmonic current in neutral conductor in (2)

$$I_{n3^{rd}} = -\left(I_{a3^{rd}} + I_{b3^{rd}} + I_{c3^{rd}} \right) \qquad (1)$$

$$I_{n3^{rd}} = -\left(I_{a3^{rd}} + I_{b3^{rd}} + I_{c3^{rd}} \right) \approx 0 \qquad (2)$$

$$I_n = \sqrt{I_a^2 + I_b^2 + I_c^2 - I_{ab} - I_{bc} - I_{ca}} \qquad (3)$$

$$I_A = i_{a1} + Sin(2\pi ft) + i_{a3} Sin(3(2\pi ft) \qquad (4)$$

$$I_B = i_{b1} + Sin(2\pi ft - 120) + i_{b3} Sin(3(2\pi ft - 120)) \qquad (5)$$

$$I_C = i_{C1} + Sin(2\pi ft + 120) + i_{C3} Sin(3(2\pi ft + 120)) \qquad (6)$$

The total harmonic percentage THD that appeared in Fig.1 is generated by

$$\%THD_1 = \frac{\sqrt{\sum_{h=2}^{\infty} I^2 h(rms)}}{I_1(rms)} \times 100\% \qquad (7).$$

2. Principles of Operation

Fig. 2 shows the arrangement of the proposed active filtering system. An active filter is placed in serial connection with the neutral conductor of the three-phase four-wire system. A Hall-effect sensor Equipment provides the measurement of the neutral conductor current i_n for the system controller. The active filter can be implemented by a hard-switched IGBT inverter operation in pulse width modulation (PWM) mode. A bypass switch automatic running is provided in case the active filter is shutdown.

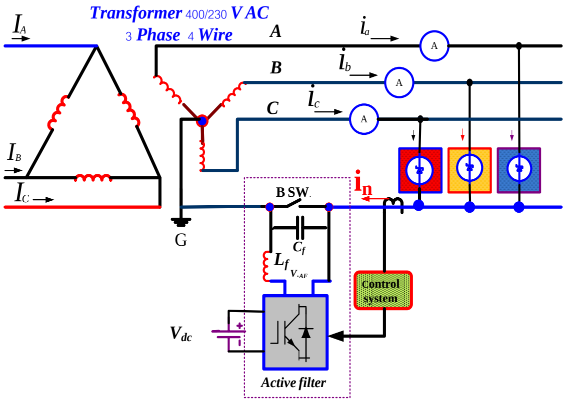


Fig.2. The proposed active filtering scheme for a three-phase four-wire distribution system.

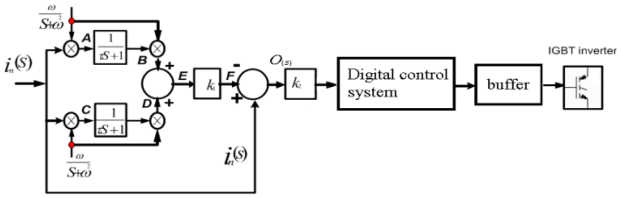


Fig.3. Controller System Design using Microprocessor.

The controller using a microprocessor chip (PIC18F2431) and an analogue circuit of the proposed system is given in Fig. 3. A multiplication process is applied to the neutral conductor current i_n to separate the fundamental and harmonic components for analysis. The current I is multiplied by sin($\boldsymbol{\omega_o}$**t**) and cos($\boldsymbol{\omega_o}$**t**) respectively where $\boldsymbol{\omega_o}$ is the frequency of the utility grid. The fundamental component of i_n is converted into DC, and the harmonics are converted into AC after the multiplication. Note that sin($\boldsymbol{\omega_o}$**t**) and cos($\boldsymbol{\omega_o}$**t**) are synchronized to the utility by a harmonic sensor using Hall-Effect Equipment. Low-pass filters (cut-off at 5 Hz) shown in Fig. 9 are applied to extract the DC components. The DC components are multiplied by sin($\boldsymbol{\omega_o}$**t**) and cos($\boldsymbol{\omega_o}$**t**) respectively and the sum to synthesize the fundamental component of i_n (represented by $i_{n,f}$). A scaling factor of 2 is for normalization. Several Synchronous Reference Frame (SRF) based active filter control schemes use similar techniques to extract the fundamental or harmonics component [17],[18],[19],[20]. This process extracts the fundamental component $i_{n,f}$ without introducing any time delay. The IRP theory used by some of the aforementioned filtering schemes is susceptible to the harmonic distortion of the utility voltages [17],[21]. The voltage command of the active filter inverter is generated by

$$V_{inv}^{*} = K_h(i_n - i_{nf}) \approx K_h \cdot i_{nh} \qquad (8)$$

where $i_{n,h}$ represents the harmonics component of i_n . The variable V^*_{inv} represents a high gain (K_h) for the current harmonics in the neutral conductor. Therefore $i_{n,h}$ will be suppressed by the active filter inverter while the fundamental component $i_{n,h}$ is not affected. The remaining $i_{n,h}$ will not overload the neutral conductor which is usually of the same size as the phase conductors. The voltage command V^*_{inv} is compared to a triangular carrier to generate the PWM gating pulses. The active filter inverter switches at 20 kHz to provide sufficient bandwidth for the desired filtering characteristics.

2.1 characteristics of circuit analysis method

The equivalent circuit of the proposed active filter system in Fig. 4,V_{AF} represents the series active filter inverter output voltage. The loads are modeled as voltage sources V_{La}, V_{Lb}, V_{Lc} and impedance Z_L. Note that the loads may be unbalanced and nonlinear. Therefore, V_{La}, V_{Lb}, and V_{Lc} may be unbalanced and may contain Z_s and Z_n which are the impedances of the phase conductors and the neutral conductor. V_{Sa} , V_{Sb} and V_{Sc} are the balanced grid voltages.

The active filter inverter is controlled as high impedance for the harmonics current component and can be expressed as

$$V_{AF} = KhG_{In} \qquad (9).$$

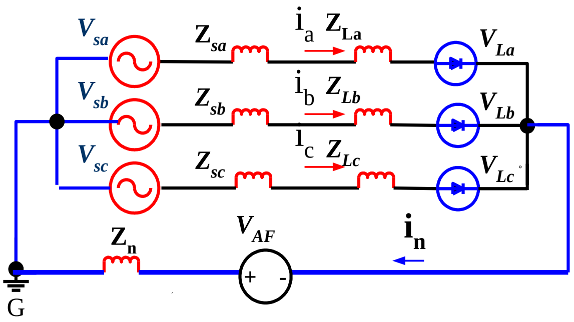


Fig.4. The equivalent circuit of the proposed active filter system.

where G is equivalent to the harmonics extraction. The series active filter expressed by V_{AF} in its equivalent circuit form is indicated in Fig 4. The relationship for the current and voltage can be expressed as follows:

$$V_{Sa} - Z_S I_a - Z_L I_a - V_{La} + V_{AF} + Z_n I_n = 0 \qquad (10)$$

$$V_{Sb} - Z_S I_b - Z_L I_b - V_{Lb} + V_{AF} + Z_n I_n = 0 \qquad (11)$$

$$V_{Sc} - Z_S I_c - Z_L I_c - V_{Lc} + V_{AF} + Z_n I_n = 0 \qquad (12)$$

$$V_{Sa} + V_{Sb} + V_{Sc} - Z_S(I_a + I_b + I_c) - Z_L(I_a + I_b + I_c) - V_{La} - V_{Lb} - V_c + 3V_{AF} + 3Z_n I_n = 0 \qquad (13)$$

when $(I_a + I_b + I_c) = I_n$ and $V_{sa} + V_{sb} + V_{sc} = 0$

For balanced load

The relationship between currents and voltages can be expressed as

$$I_n = \frac{V_{La} + V_{Lb} + V_{Lc}}{Z_s + Z_L + 3Z_N + 3_{Kh}G} \qquad (14).$$

Note that the zero sequence of the grid voltages does not exist because V_{Sa} , V_{Sb} and V_{Sc} are assumed to be balanced. With a large gain of K_h , the active filter inverter emulates a high resistance at the harmonic frequencies. Therefore, the harmonic components of the neutral current I_n can be suppressed. Series active filters are more suitable for nonlinear loads characterized by harmonic voltage sources [20] such as diode rectifiers with smoothing DC bus capacitors widely used in electronics equipment.

3. Test Equipment and Results

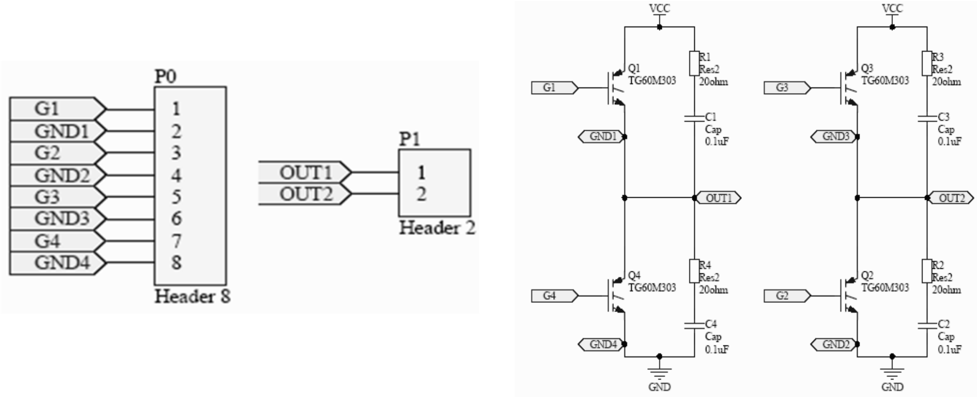
The experimental equipment is shown in Fig. 5. The system parameters used in the test are given as follows.

(A) Power and control system (B) Nonlinear load

Fig.5. The system parameters used in the test Fig (A) shows power and control system Fig (B) nonlinear load RC.

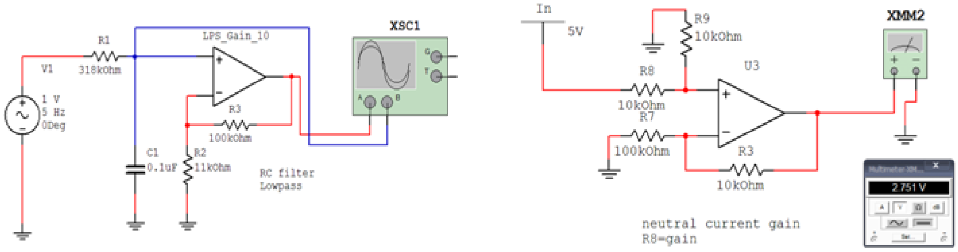
Fig.6. The experimental instruments.

- Power supply: 220V(line-neutral, RMS), 50Hz, L_s =0.65 mH.
- Active filter: by IGBTs, hard-switched PWM operation with switching frequency (IGBT converter- GT-60M303Q /60A-900 V)
- Harmonic sensor equipment using Hall-Effect /output voltage
- Control system by microprocessor (PIC18F2431)/ISO 124
- DC capacitor, filter and line reactor



(A) (B)

Fig.7. (A) The microprocessor circuit controller (PIC18F2431) (B) Circuit IGBT Converter-GT-60M303Q /60A-900V Circuit diagram for controller and converter.



(A) Low pass filter Frequency cut off at 5 Hz. (B) Neutral current adjustment

Fig.8. Circuit diagram for measuring low frequency and neutral current.

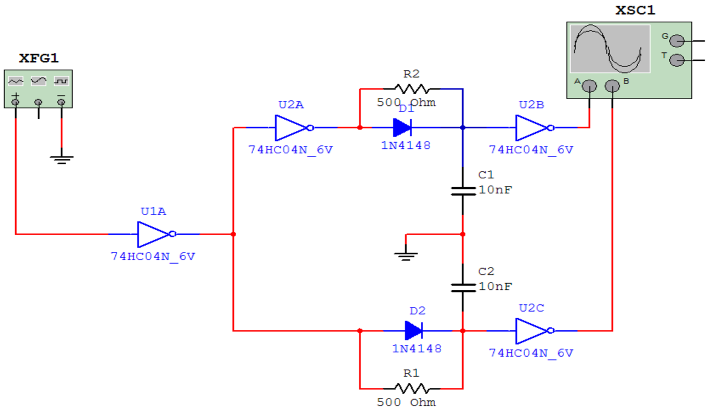


Fig.9. Circuit dead time for IGBT switching (G1,G3 and G2,G4).

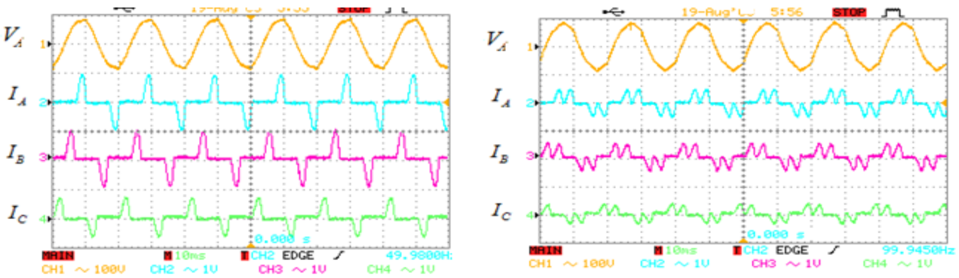


Fig.10. Balanced load V_A, I_A, I_B and I_C (A) before active filter is started and (B) after active filter inverter is started.

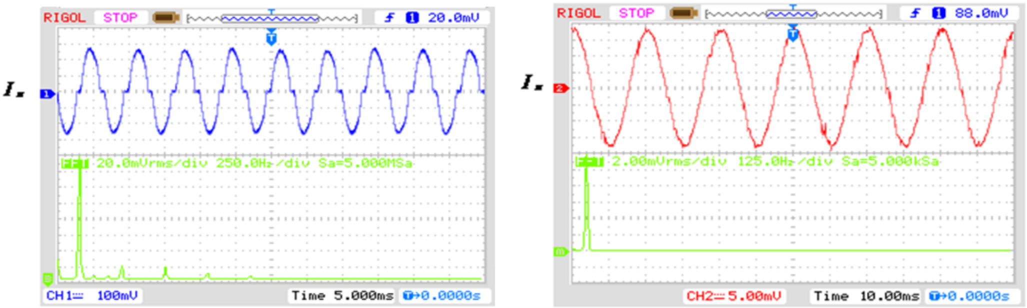


Fig.11. Balanced load current I_n (A) before active filter is start and (B) after active filter inverter is started.

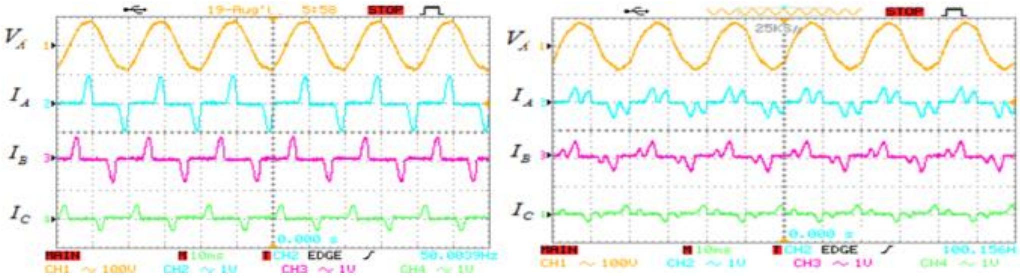


Fig.12. Unbalanced load current flow in V_A,I_A, I_B and I_C (A) before active filter is startd and (B) after active filter inverter is started.

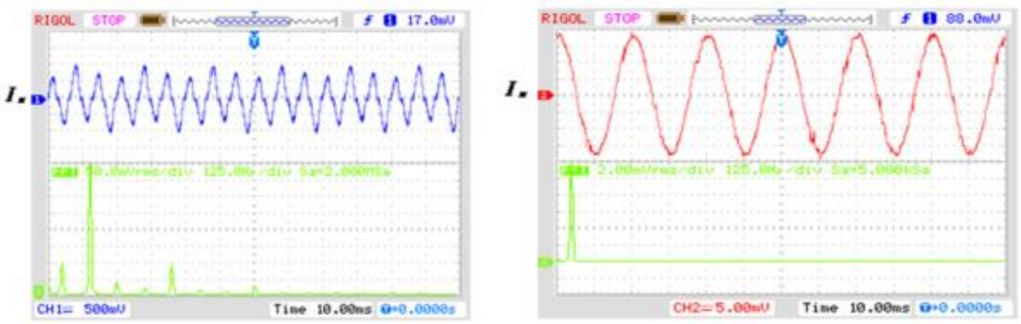


Fig.13. Unbalanced load current I_n (A) before active filter is started and (B) after active filter inverter is started.

Table 1. Balanced loading.

Power	R (Ω)	C ($\mu F.$)	kW
Phase A	50	1200	0.5
Phase B	50	1200	0.5
Phase C	50	1200	0.5

Table 2. Unbalanced loading.

Power	R (Ω)	C ($\mu F.$)	kW
Phase A	50	1200	0.5
Phase B	25	1200	1
Phase C	15	1200	1.5

Table 3. Results of THD % before and after active filter is started under balanced and unbalanced load.

THD (%) in a neutral conductor	**Balanced load (%)**	**Unbalanced load (%)**
Before active filter is started	25	32
After active filter is started	0	2

4. Conclusions

An active filter mitigation technique for three-phase four-wire distribution systems is proposed in this paper. The proposed system uses a series active filter inverter in the neutral conductor to mitigate the current harmonics. The controller of the active filter system mitigated the current harmonics by using an analogue circuit and microprocessor controler. The active filter comprises IGBT Converter- GT-60M303Q /60A-900 V. Therefore, the harmonics distortion of the neutral conductor current is reduced while the fundamental component remains unaffected. The resulting harmonic and fundamental current originated from unbalanced loading will not be overloaded. The balanced load before deploying the active filter THD is 25%. It became zero after using the active filter. The unbalanced load before applying the active filter THD is 32%. It became 2 % after using active filter. When compared to other shunt active filter systems, the proposed series active filter can mitigate current harmonics for the entire neutral conductor and the distribution transformer within a single installation. Test results validate the operation of the proposed system. In future development, an accurate control system must be equipped to “dSPACE” Desk or DSP hardware.

5. References

[1] Sekar, T.G., Series Active Filter for three-phase-four-wire distribution system using Artificial Neutral Network. European Journal of Scientific Research, Vol.79, No.4, pp.507-518, 2012.

[2] Hang, T.Y. and Hon, C.C., A new Harmonic suppression scheme for three-phase-four-wire distribution system, in Proc.of IEEE APEC, pp. 1287-1293, 2001.

[3] Gruzs, T.M., A survey of neutral currents in three-phase computer power systems, IEEE Transactions on Industry Applications, vol. 26, no. 4, pp.719-725, July/August 1990.

[4] Liew, A.C., Excessive neutral currents in three-phase fluorescent lighting systems, IEEE Transactions on Industry Applications, vol.25, no. 4, pp.776-782, July/August 1989.

[5] Khera, P.P., Application of zigzag transformers for reducing harmonics in the neutral conductor of low voltage distribution system, in Proc. of IEEE/IAS, pp.1092, 1990.

[6] Aredes, M. and Watanabe, E. H., New control algorithms for series and

shunt three-phase-four-wire active power filters,” IEEE Transactions on Power Delivery, vol.10, no.3, pp.1649-1656, July 1995.

[7] Aredes, M., Hafner, J. and Heumann, K., Three-phase-four-wire shunt active filter control strategies, IEEE Transactions on Power Electronics, vol.12, no. 2, pp.311-318, March 1997.

[8] Quinn, C.A., Mohan, N. and Mebta, H., A four-wire-current-controlled converter provides harmonic neutralization three-phase-four-wire systems,” in Proc. of IEEE APEC, pp. 841-846, 1993.

[9] Dastfan, A., Platt, D. and Gosbell, V. J., Design and implementation of a new three-phase-four-wire active power filter with minimum components, in Proc. of IEEE/IAS, pp.1369-1376, 1998.

[10] Kamath, G., Mohan, N. and Albertson, V.D., Hardware implementation of a novel reduced rating active filter for 3phase- 4wire loads, in Proc. of APEC, pp. 984-989, 1995.

[11] Enijeti, P., Packebush, P. and Pitel, I., Analysis and design of a new active power filter to cancel neutral current harmonics in three phase four wire electric distribution systems, in Proc. of IEEE/IAS., pp. 939-946, 1993.

[12] Akagi, E., Kanazawa, Y. and Nabae, A., Instantaneous reactive power compensators comprising witching devices without energy storage components, IEEE Transactions on Industry Applications, vol. 20, no. 3, pp. 625-630, May/June 1984.

[13] Peng, F.Z. and Lai, J.S., Generalized instantaneous reactive power theory for three-phase power systems, IEEE Transactions on Instrumentation and Measurement, Vol. 45, no. 1, pp. 293-297, February 1996.

[14] Peng, F.Z., Akagi, H. and Nabae, A., A new approach to harmonic compensation in power systems - a combined system of shunt passive and series active filters, IEEE Transactions on Industry Applications, Vol. 26, No. 6, pp. 983-990, November/December 1990.

[15] Fujita, H. and Akagi, H., An approach to harmonic-free ac/dc power conversion for large industrial loads: the integration of a series active filter with a double-series diode rectifier, in Proc. of IEEE/IAS, pp. 1040-1047, 1996.

[16] Bhattacharya, S. and Divan, D., Design and implementation of a hybrid series active filter system, in Proc. of IEEE/PESC, pp. 189-195, 1995.

[17] Bhattacharya, S. and Divan, D., Synchronous frame based controller implementation for a hybrid series active filter system, in Proc. of IEEE/IAS, pp. 2531-2540, 1995.

[18] Bhattacharya, S., Frank, T.M., Divan, D.M. and Banerjee, B., Active filter system implementation, IEEE Industry Applications Magazine, vol.4, no.5, pp. 47-63, September/ October 1998.

[19] Cheng, P. T., Bhattacharya, S. and Divan, D., Hybrid solutions for improving passive filter performance in high power applications, in Proc. of IEEE/APEC, pp. 911-917, 1996.

[20] Cheng, P. T., Bhattacharya, S. and Divan, D., Experimental verification of dominant harmonic active filter for high power applications. IEEE Transactions on Industry Applications. Vol.36, no.2, March/ April 2000.

[21] Bhattacharya, S., Divan, D. and Banerjee, B., Synchronous frame harmonic isolator using active series filter, in Proc. of IPE ’91, pp. 30-35, 1991.

[22] Peng, F.Z., Application issues of active power filters, IEEE Industry Applications Magazine, Vol.4, No. 5, pp, 21-30, September/October 1998.