New Control Technique for Compensation of Neutral Current Harmonics in Three-Phase Four-Wire Systems

J. Keramati Zadeh and E. Farjah

Abstract--**Use of Nonlinear loads such as power electronic converters, power supplies used in personal computers and etc is the main cause of harmonics in power distribution systems. Hence, voltage distortion on utility outlets and excessive neutral current on distribution lines have arisen and lead to a number of serious problems in distribution systems.**

In this paper, a series active filter is proposed to be placed in neutral of a three-phase, four-wire distribution system. This filter interacts with neutral by injecting proper current in order to suppress the excessive current harmonics, this in turn will prevent the overloading of the neutral conductor and the distribution transformer. Detailed analysis of the proposed system will be presented. Also a new control method and the related compensation characteristics of a series active filter connected in the neutral conductor are presented in this paper. This approach has been simulated using MATLAB.

Index Terms--**Harmonic voltage distortion, neutral conductor, nonlinear loads, series active filter, third harmonic.**

I. INTRODUCTION

THE use of non-liner loads, such as adjustable speed drives and computer equipment is growing rapidly. These equipments draw distorted currents from distribution feeders and also from distribution transformers. This in turn will cause a flow of harmonic currents through distribution equipments which lead to their heating. Because of load unbalance the zero sequence triple harmonics accumulate in the neutral conductor, thus result in overloading of the neutral conductor and the distribution transformer.

Especially on three-phase four-wire distribution systems, the third-harmonic currents are increased. The excessive third harmonic currents cause overheating of the neutral conductors [1]. In order to reduce the neutral current, a passive filter connected in series with the neutral conductor could be used [2]. Recently, several schemes have been proposed to reduce the current harmonics of the neutral conductor, such as zig-zag transformer arrangement [3], active filter systems based on power electronics components [4-7], and combination of both [8-9]. The Instantaneous Reactive Power theory [10-ll] has been adopted to calculate the harmonics compensation command for some of the aforementioned schemes. Also in [12-13] series active filters are proposed to be placed in neutral of a three-phase, four-wire distribution system.

Comprehensive details of conventional control method and it's analysis with synchronous reference frame is presented in [14].

In this paper, a new harmonic suppression scheme for the neutral conductor of three-phase, four-wire distribution systems is proposed. The proposed system applies on an active filter inverter connected in series with the neutral conductor to suppress the zero sequence current harmonics of the neutral conductor. Elaborated analysis of the proposed method will be presented to validate the filtering performance of the proposed system.

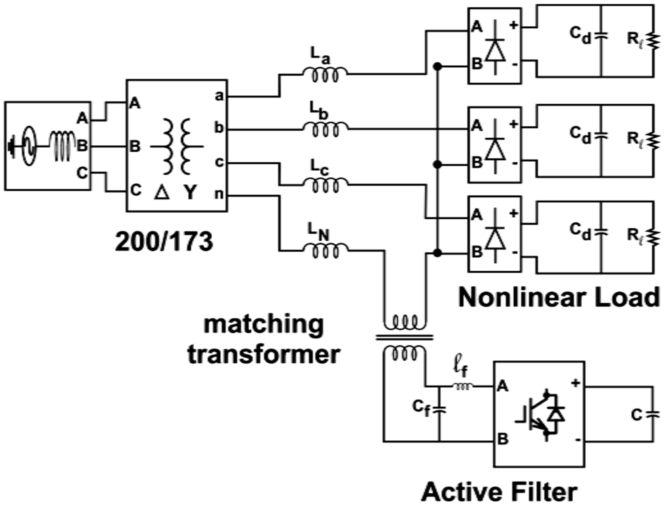


Fig.1.The proposed active filtering scheme for a three phase four-wire distribution system

II. SYSTEM CONFIGURATION

Fig. 1 shows the 5-kVA small-scaled model of a three phase, four-wire distribution system. An active filter is placed in serial connection with the neutral conductor of the three phase four-wire system. A sensor provides the measurements of the neutral conductor current i_n and neutral conductor voltage v_n for the system controller. Table 1 shows the circuit parameters of this model. The model consists of a Δ–Y step-down transformer, three nonlinear loads, and an active filter. The nonlinear loads, each of which consists of a diode rectifier and parallel RC load. The active filter is connected in series with the neutral conductor via a switching-ripple $LC\psi$filter $L_{f\psi}$and

---

J. keramati zadeh is with the Electrical & Computer Engineering department of, Shiraz University, Shiraz, IRAN (e-mail: jafar.keramati@gmail.com).
E.farjah is with the Electrical & Computer Engineering department of Shiraz University, Shiraz, IRAN (e-mail: farjah@shirazu.ac.ir).

Cfψ and a matching transformer (MT). A bypass switch is provided in case the active filter is shutdown.

TABLE I
PARAMETERS OF THE CIRCUIT IN FIG.1

Capacity of Δ-Y transformer	5 kVA
Resistance of the Δ-Y transformer, Rs	0.25 Ω
Inductance of the Δ-Y transformer, Ls	0.17 mH
Line-to-neutral voltage	100 V
Active power of the loads	2.6 kw
Capacitance of the load rectifiers	100 µF
Carrier frequency of the inverter	20 kHz
Cutoff frequency of the LC filter	11.3 kHz
Turn ratio of MT	1:5
Rated dc capacitor voltage	160 V
Dc capacitance	100 µF

.

III. METHOD OF THIRD-HARMONIC

A. *METHOD OF NEUTRAL CURRENT REDUCTION*

Fig. 2 shows the zero-sequence equivalent circuits of Fig. 1 when the active filter reduces the neutral current. The loads are modeled as voltage sources V_{La}, V_{Lb}, V_{Lc} and impedance Z_L ,Z_s and Z_n are the impedances of the phase conductors and the neutral conductor. V_{sa} , V_{sb} and V_{sc} are the balanced grid voltages. V_{AF} represents the series active filter inverter output voltage, which has the following characteristics:

$$\mathrm{V_{AF}} = \mathrm{k_r I_N} \quad (1)$$

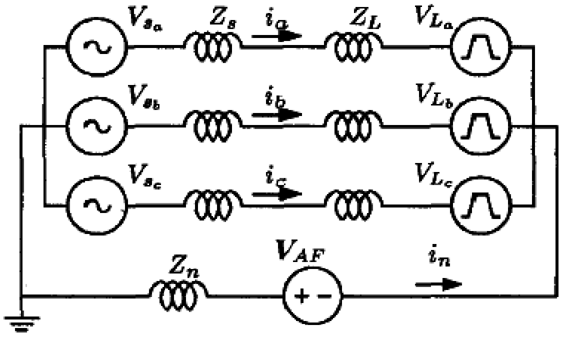


Fig. 2. The zero-sequence equivalent circuit.

The active filter inverter presents a high impedance $\mathrm{k_r}$ at harmonic frequencies to suppress current harmonics in the neutral conductor. The relationship of currents and voltages can be expressed as:

$$\mathrm{V_{sa} - Z_{sa}I_a - Z_{la} - V_{la} + V_{AF} = 0} \quad (2)$$
$$\mathrm{V_{sb} - Z_{sb}I_b - Z_{lb} - V_{lb} + V_{AF} = 0} \quad (3)$$
$$\mathrm{V_{sc} - Z_{sc}I_c - Z_{lc} - V_{lc} + V_{AF} = 0} \quad (4)$$

The source impedances of the ac grid are usually balanced; Therefore $Z_{sa}= Z_{sb}= Z_{sc}= Z_s$ is assumed. Z_{La} , Z_{Lb} , and Z_{Lc} are all equated to a small impedance Z_L. By summing up (2), (3) and (4), and applying the above assumptions, the neutral conductor current I_N can be derived as

$$\mathrm{I_N} = \frac{\mathrm{(V_{la} + V_{lb} + V_{lc}) - (V_{sa} + V_{sb} + V_{sc})}}{\mathrm{Z_s + Z_l + 3K_r}} \quad (5)$$

With a large gain $\mathrm{k_r}$, 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.

B. *Controller of the Active Filter for Third-Harmonic Reduction*

Fig. 3 shows the controller of the active filter for the third harmonic current mitigation. Control of the active filter is performed on a rotating frame synchronized with the third-harmonic frequency (180HZ). The voltage and current of neutral point, v_N andψ i_N is transformed into orthogonal quantities v_N ψ ,v_N ψ ψ andψ i_N ψ ‘ψ $i_{N\,\psi}$ by a time-derivative element:

$$\begin{bmatrix} v_{\mathrm{N\alpha}} \\ v_{\mathrm{N\beta}} \end{bmatrix} = \begin{bmatrix} 1 \\ -\frac{1}{\omega_3}\frac{\mathrm{d}}{\mathrm{dt}} \end{bmatrix} \mathrm{v_N} \quad (6)$$

$$\begin{bmatrix} i_{\mathrm{N\alpha}} \\ i_{\mathrm{N\beta}} \end{bmatrix} = \begin{bmatrix} 1 \\ -\frac{1}{\omega_3}\frac{\mathrm{d}}{\mathrm{dt}} \end{bmatrix} \mathrm{i_N} \quad (7)$$

Note that the frequency $\omega_3$of the neutral current can be obtained by a phase-locked-loop (PLL) circuit. By means of signal generation building base signal sin 3t and cos 3t, then α and β components are transformed into d and q synchronous reference frame. By useing synchronous reference frame $i_{N\alpha}$ and $i_{N\beta}$ψ transformed into i_{Nd} and i_{Nq} synchronous reference frame as

$$\begin{bmatrix} i_{\mathrm{Nd}} \\ i_{Nq} \end{bmatrix} = \begin{bmatrix} \cos\theta_{3i} & \sin\theta_{3i} \\ -\sin\theta_{3i} & \cos\theta_{3i} \end{bmatrix} \begin{bmatrix} i_{N\alpha} \\ i_{N\beta} \end{bmatrix} \quad (8)$$

Instantaneous real power ($\mathrm{P_{\alpha\beta}}$), imaginary power (q) are calculated as Eq. (9).

$$\begin{bmatrix} p_{\alpha\beta} \\ q \end{bmatrix} = \begin{bmatrix} v_{\mathrm{N\alpha}} & v_{\mathrm{N\beta}} \\ -v_{\mathrm{N\beta}} & v_{\mathrm{N\beta}} \end{bmatrix} \begin{bmatrix} i_{\mathrm{Nd}} \\ i_{\mathrm{Nq}} \end{bmatrix} \quad (9)$$

The instantaneous real and imaginary powers include AC and DC values and can be expressed as follows:

$$\begin{aligned} p_{\alpha\beta} &= \bar{p} + \tilde{p}_{\alpha\beta} \\ q &= \bar{q} + \tilde{q} \end{aligned} \quad (10)$$

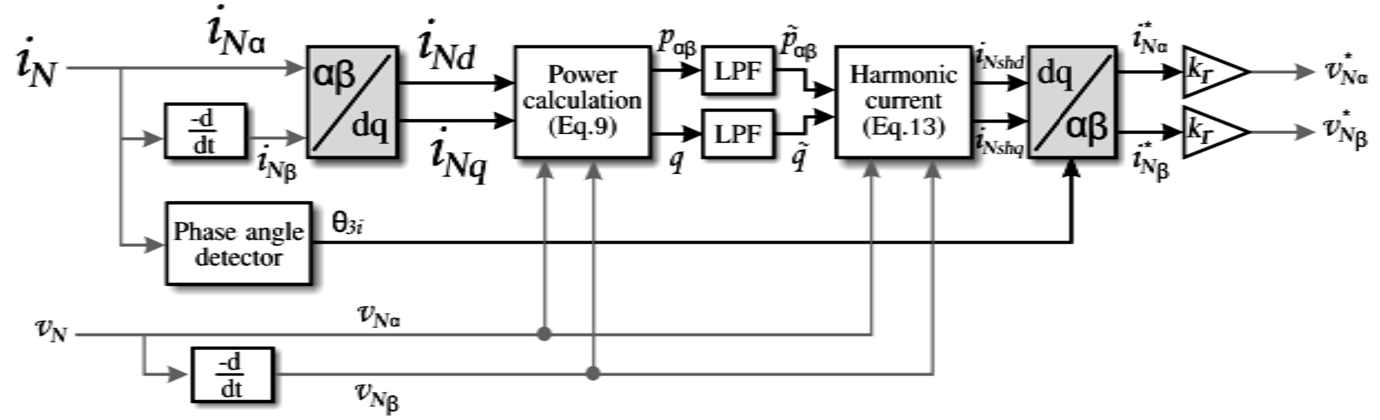


Fig. 3. The Block diagram of the controller for the mitigation of third-harmonic voltages

DC values ($\bar{p}, \bar{q}$) of the $p_{\alpha\beta}$ and q are the average active and reactive power.AC values ($\tilde{p}, \tilde{q}$) of the $p_{\alpha\beta}$ and q are the ripple active and reactive power originating from harmonic of the neutral current. Thus, $p_{\alpha\beta}$ and q signals are filtered, using high pass filters (HPF) with cut-off frequency at 200HZ which enables to obtain $\tilde{p}, \tilde{q}$. With these signals and prementioned equations, all of harmonic currents with a frequency higher than base frequency, can be compensated. If harmonic currents in d-q reference frame considers as follow:

$$i_{\mathrm{Nshd}} = \sum_{n=2}^{\infty} \mathrm{I}_{\mathrm{dn}} \qquad (11)$$

$$i_{\mathrm{Nshq}} = \sum_{n=2}^{\infty} \mathrm{I}_{\mathrm{qn}} \qquad (12)$$

Eq. (11) and (12) represent the required compensating current references in d-q coordinate. Then substituting $\tilde{p}, \tilde{q}$, i_{Nshd} and i_{Nshq} respectively instead of $p_{\alpha\beta}$, q, iNd and iNq in equation (9) and inversing voltage coefficients matrix, it could be seen that:

$$\begin{bmatrix} i_{\mathrm{Nshd}} \\ i_{\mathrm{Nshq}} \end{bmatrix} = \frac{1}{v_{\mathrm{N}\alpha}^2 + v_{\mathrm{N}\beta}^2} \begin{bmatrix} v_{\mathrm{N}\alpha} & -v_{\mathrm{N}\beta} \\ v_{\mathrm{N}\beta} & v_{\mathrm{N}\alpha} \end{bmatrix} \begin{bmatrix} \tilde{p}_{\alpha\beta} \\ \tilde{\mathrm{q}} \end{bmatrix} \quad (13)$$

Achieved currents are considered as active filter compensating reference. Hence applying inverse stationary frame on i_{Nshd} and i_{Nshq}, compensating reference currents in α-β coordinating could be calculated.

$$\begin{bmatrix} i^*_{\mathrm{N}\alpha} \\ i^*_{\mathrm{N}\beta} \end{bmatrix} = \begin{bmatrix} \cos\theta_{3i} & -\sin\theta_{3i} \\ \sin\theta_{3i} & \cos\theta_{3i} \end{bmatrix} \begin{bmatrix} i_{\mathrm{Nshd}} \\ i_{\mathrm{Nshq}} \end{bmatrix} \quad (14)$$

Then calculated compensating harmonic current in α-β coordinate are multiplied by resistance coefficient to calculate reference voltages, $v^*_{\mathrm{N}\alpha}$ and $v^*_{\mathrm{N}\beta}$, as follow:

$$\begin{bmatrix} v^*_{\mathrm{N}\alpha} \\ v^*_{\mathrm{N}\beta} \end{bmatrix} = \mathrm{K}_{\mathrm{r}} \begin{bmatrix} i^*_{\mathrm{N}\alpha} \\ i^*_{\mathrm{N}\beta} \end{bmatrix} \qquad (15)$$

The command voltages $v^*_{\mathrm{N}\alpha}$ and $v^*_{\mathrm{N}\beta}$ are compared with a 20-kHz triangular-wave signal and generated inverter operating in pulse width-modulation (PWM) mode.

IV. SIMULATION RESULTS

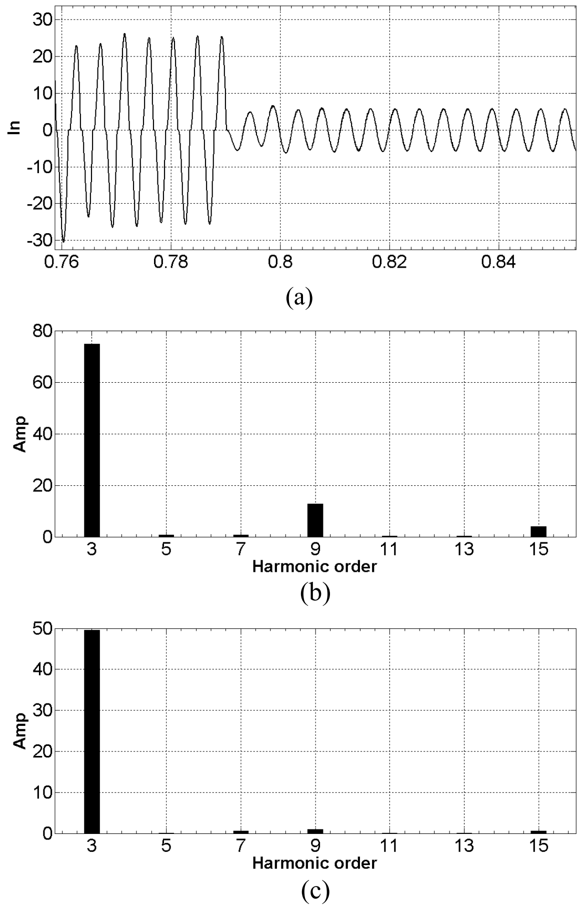
The simulated circuit is shown in figure 1. The system parameters used in the simulation are given as follows:
Supply: 120Vrms (line-neutral), 60Hz, Ls=0.35mH which represents the leakage inductance of the distribution transformer and the utility inductance.
Active filter: A H-bridge inverter using IGBTs, and PWM operation with switching frequency of fsw=20 kHz,
output filter: consists of Lf = 0.2mH, Cf = 1.0μF.

$$\omega_0 = \frac{1}{\sqrt{\mathrm{lc}}} = 70.7 \times 10^3 \ \mathrm{rad/sec}\,(11.3\ \mathrm{k\,H\,z})$$

A. Balanced load

In this test, the rectifier loads on all three phases are balanced and approximately 1.7 kW. $\mathrm{Cdc_a}=\mathrm{Cdc_b}=\mathrm{Cdc_c}$ = 15OOμF, $\mathrm{Rload_a} = \mathrm{Rload_b} = \mathrm{Rload_c} = 25\Omega$. i_N waveform obtained from simulation and its spectra is shown in figure 4. The zero sequence triplen harmonics accumulate in the neutral conductor, thus result in a severely distorted current waveform. The 3rd harmonic component shown in figure 4(b) is slightly less than 80A. As the active filter starts at t=0.8sec., the harmonics of i_N current are greatly reduced as shown in figure 4(c).

Figures 5 and 6, show the waveforms and the spectra of the phase currents ia before applying the active filter. The phase current contain significant 3rd harmonic current which is typical for single-phase diode rectifiers. The THD of the phase current is 112.92%. Since the active filter inverter suppresses the zero sequence harmonics current in the neutral conductor, such components are suppressed in the phase conductors as well. Comparing the spectra of figure 6 (before) and figure 7 (after), the zero sequence harmonics such as the 3th, and the 9th are significantly reduced by the active filter inverter, while all other components remain almost unchanged. The THD of the phase current is also reduced to 65.77%. All of simulations are performed with MATLAB Simulink package.



(a)

(b)

(c)

Fig. 4. Neutral current i_N; (a) balanced loading, (b) Before the active filter is started, (c) After the active filter

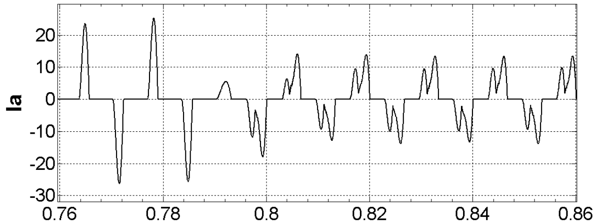


Fig. 5. Phase conductor current ia (balanced loading).

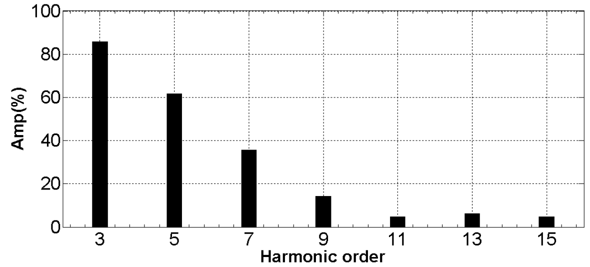


Fig. 6. Spectra of ia before applying active filter (balanced loading).

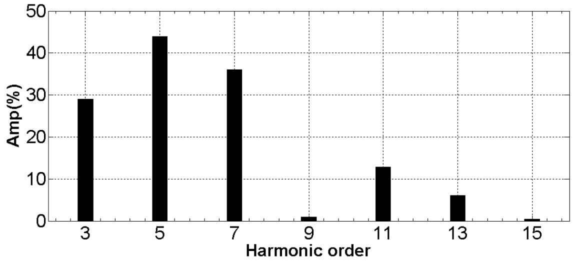
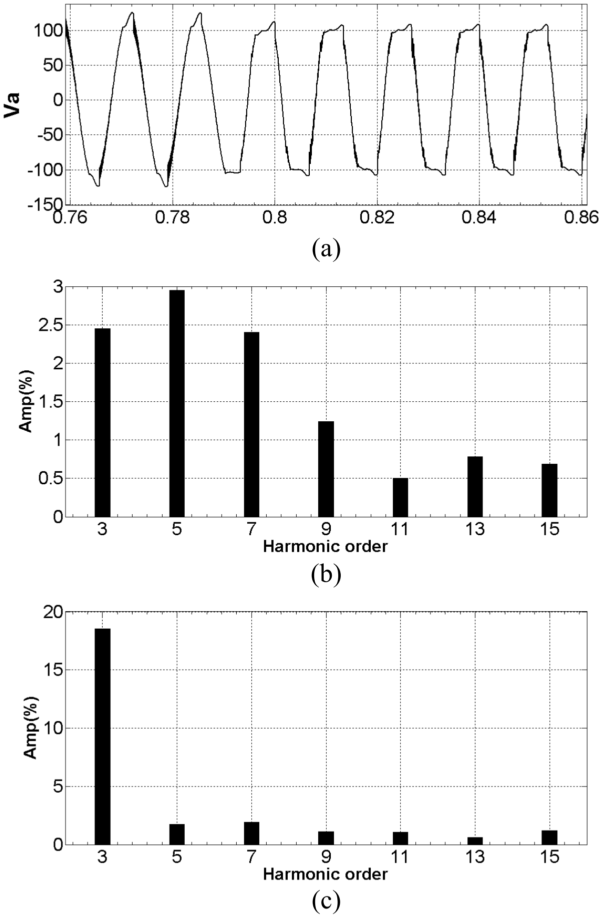


Fig. 7. Spectra of ia after applying active filter (balanced loading).

Figure 8(a) shows the waveform of phase to neutral voltage V_a before and after applying active filter inverter. The “flat-topping” of the V_a results from the third harmonic component of V_{inv}. The spectra of V_a [Figure 8(b) and (c)] also indicates a significant increase of the third harmonic component after the active filter inverter is applied.



(a)

(b)

(c)

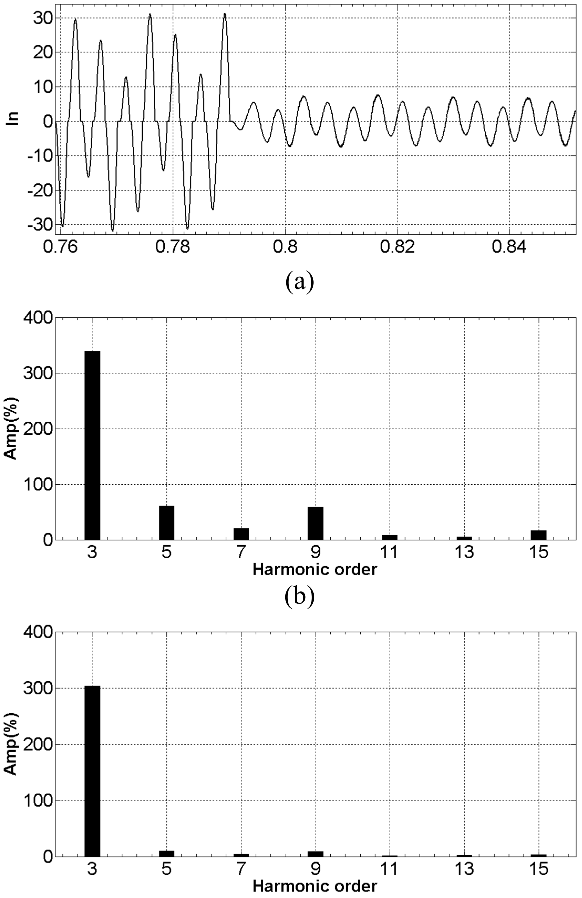
Fig. 8. (a) phase to neutral voltage Va (b) spectrum before applying active filter (c) spectrum after applying active filter.

B. Unbalanced load

In this test, the rectifier loads are unbalanced.
Phase A: 257W, Cdc_a = 15OOμF, $Rload_a$ = 56Ω.
Phase B: 576W, Cdc_b = 15OOμF, $Rload_b$ = 25Ω.
Phase C: 757W, Cdc_c = 15OOμF, $Rload_c$ = 19Ω.

The neutral conductor current i_N contains approximately 6.5 A of fundamental component as indicated in figure 9(a). Due to the zero sequence harmonic component produced by the rectifier load, the peak value of i_N reaches 30A. Figure 9(b) shows the spectrum of $i_{N\psi}$ before applying filter. The Total Harmonic Distortion (THD) factor of i_N exceeds 300% due to the severe harmonic distortion.

After applying the active filter at around t = 0.8 sec., the harmonics of i_N is significantly reduced as shown in figure 9(c) compared to figure 9(b). The fundamental component of i_N caused by unbalance loading is not affected by the active filtering operation. The THD of i_N is reduced to approximately 13.45% .Figure 10 shows the output voltage of the active filter inverter.



(a)

(b)

(c)

Fig. 9. (a) Neutral current waveform of i_N, (b) spectrum of i_N before applying filter, (c) spectrum of i_N after applying active filter

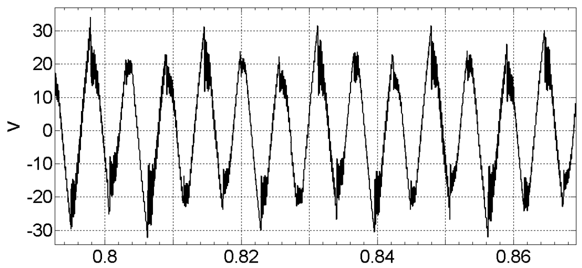


Fig. 10. Active filter inverter output voltage

Figure 11 shows the waveforms of unbalanced phase currents *ia*, *ib* and *ic*. Figure 12 shows the spectrum of the phase currents *ia*, *ib* and *ic* before applying the active filter inverter. The THDs of the phase currents are 129.24%, 114.4%, and 107.24% for *ia*, *ib* and *ic* respectively.

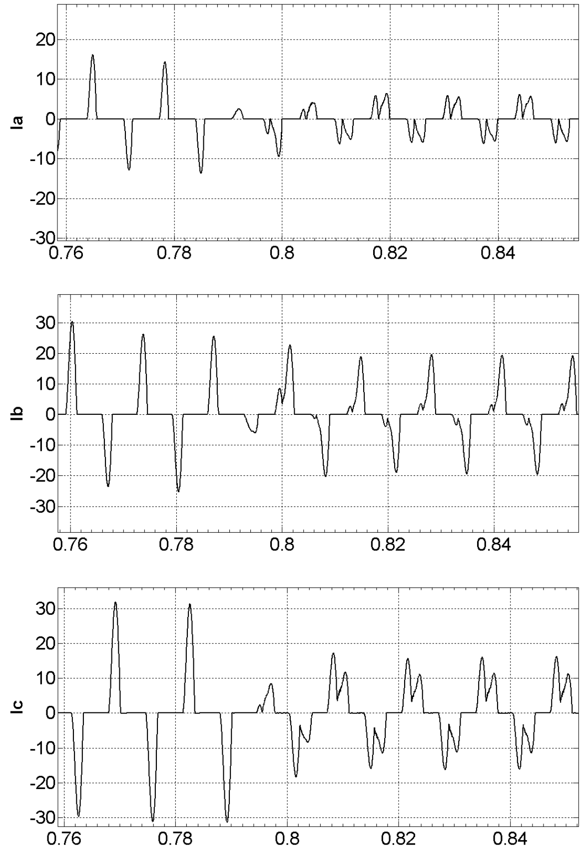


Fig. 11. Phase conductor currents ia, ib, ic (unbalanced loading).

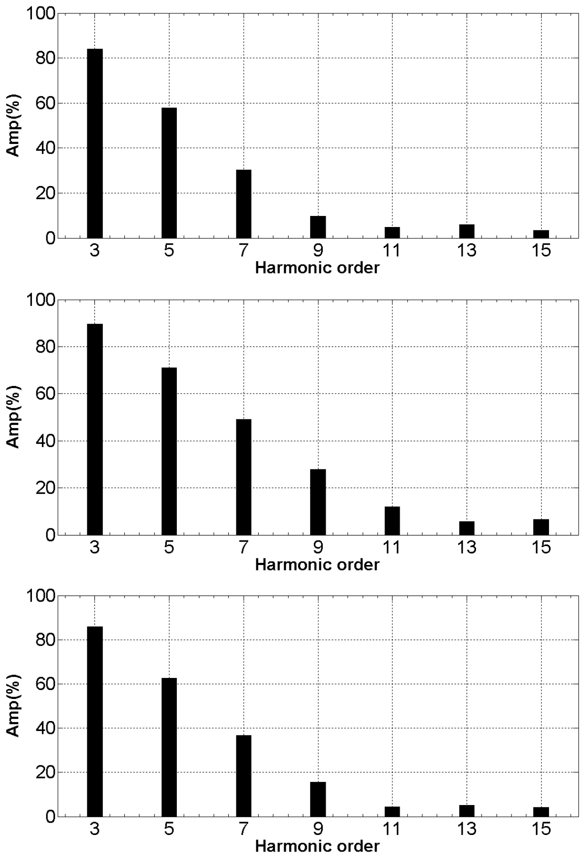


Fig. 12. Spectra of *ia, ib, ic* ; before applying the active filter (unbalanced loading).

Figure 13 shows the spetra of the phase currents *ia*, *ib* and *ic*, after the active filter inverter is applied. The THDs are reduced to 71.03%, 90%, and 58.58% respectively. It should be mentioned that the magnitude of the 3rd harmonic in phase conductors are also reduced by the operation of the active filter inverter.

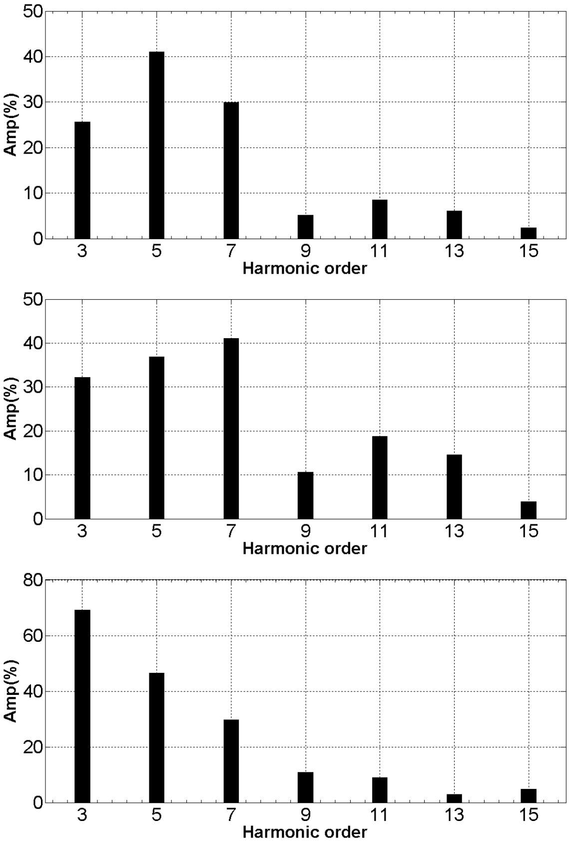


Fig. 13. Spectra of ia, ib, ic ; after applying the active filter (unbalance loading).

V. CONCLUSION

The controller of the active filter system extracts neutral current and voltage harmonics by using a stationary frame reference applied in third harmonic (180 Hz). The active filter inverter then plays the role of a variable impedance for the current harmonics.

Therefore, the harmonic distortion of the neutral conductor current is reduced. The proposed series active filter can simultaneously reduce current harmonics for the entire neutral conductor and the distribution transformer. The method is applicable for either balanced or unbalanced loading. Simulation results show the effectiveness of proposed method and suitability of control strategy for reducing harmonics in neutral conductor in three phase four wire systems.

I. References

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

[2] T. Key and J. S. Lai, “Analysis of harmonic mitigation methods for building wiring systems,” IEEE Trans. Power System., vol. 13, no. 3, pp. 890–897. 1996

[3] P. P. Khera, “Application of zigzag transformers for reducing harmonics in the neutral conductor of low voltage distribution system,” in IEEE/IAS Conference Proceedings. IEEE, pp. 1092, 1990.

[4] M. Aredes and E. H. Watanabe, “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

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

[6] C. A. Quinn, N. Mohan, and H. Mehta, “A four-wire, current controlled converter provides harmonic neutralization in three phase, four-wire systems,” proceedings of APEC. Conference, pp. 841-846, 1993.

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

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

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

[10] H. Akagi, Y. Kanazawa, and A. Nabae, “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.

[11] F. Z. Peng and 3. S. Lai, “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.

[12] P-Tai Cheng Yung-Fu Huang Chung-Chuan Hou, "Design of a neutral harmonic mitigator for three-phase four-wire distribution systems," in Proc. IEEE/IAS Annu. Meeting, vol. 1, pp.164-171, 2001.

[13] H. Fujita and H. Akagi, “An approach to harmonic current-free ac/dc power conversion for large industrial loads: The integration of a series active filter with a double-series diode rectifier,” IEEE Trans. Ind. Appl.,vol. 33, no. 5, pp. 1233–1240, Sep./Oct. 1997.

[14] Shigenori Inoue, Toshihisa Shimizu, Keiji Wada, "Control Methods and Compensation Characteristics of a Series Active Filter for a Neutral Conductor" IEEE Trans. On Industrial Electronics, vol. 54, no. 1, pp.433-439, Feb. 2007.

VI. BIOGRAPHIES

Jafar keramati zadeh received the B.S degree in power system from Electrical Engineering Department of Azad University of Yazd in 2003. Presently; he is currently student of Master Degree in Electrical & Computer Engineering department of Shiraz University His research interests are in the application of artificial intelligence in power system, power quality, fuzzy logic system, active filter , and renewable energy.

Ebrahim Farjah obtained his B. Sc. Degree in Electrical and Electronics engineering from Shiraz University, Shiraz-Iran in 1987 and his M. Sc. Degree in Electrical Power engineering from Sharif University of Technology in 1989, Tehran-Iran and his Ph.D. in electrical Engineering from INPG, Grenoble-France. He is currently associate professor in Electrical & Computer Engineering department of Shiraz University. His research field includes Electrical Machines and drive, power Electronics and power quality.