Analysis and Control of a Single-Phase-Inverter–Zigzag-Transformer Hybrid Neutral-Current Suppressor in Three-Phase Four-Wire Systems

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***Abstract*—This paper presents analysis and control of a hybrid filter that can suppress neutral harmonic currents in three-phase four-wire systems not only with harmonic voltage–source loads but also with harmonic current–source loads. The filter voltampere rating is significantly reduced compared to the conventional neutral-current-suppressing methods. The rectifier part of the neutral harmonic suppressor has been removed by controlling the dc capacitor voltage. The experimental results on a 50-kVA prototype validate the proposed control approach.**

***Index Terms*—Active filter, neutral current, three-phase four-wire, zero-sequence, zigzag transformer.**

I. INTRODUCTION

LOW-VOLTAGE three-phase four-wire electrical distribution systems have been widely employed to deliver electric power to single-phase and/or three-phase loads in manufacturing plants and commercial and residential buildings. The most common loads that are connected to the distribution system are nonlinear and include computer systems, uninterrupted power systems, adjustable-speed heating ventilation and air-conditioning systems, electronic and magnetic ballasts, photocopiers, etc. Nonlinear loads result in significant neutral current in the three-phase four-wire system since triplen odd harmonics in phase currents do not cancel each other even under balanced condition and are added up in the neutral line. In many cases, the neutral current exceeds the phase current. Under the worst case, the neutral current could be 1.73 times the phase current [1]. Excessive neutral currents may cause wiring failure of the neutral conductor, overloading of the distribution transformer, and a voltage drop between the neutral and the ground. Recently, an analysis has been performed to investigate the effect of unbalanced supply voltage and background voltage harmonics on the phase and neutral-current harmonics in the three-phase four-wire system [2].

Several methods have been proposed to reduce the neutral-current harmonics [3]–[15]. A passive zigzag transformer, which is shunt connected to the load, is designed to have a low zero-sequence impedance, allowing the zero-sequence neutral currents to circulate from the neutral back to the load [3]–[5]. This requires special design of the transformer for low zero-sequence impedance, and therefore, the size and weight of the zigzag transformer become significant. Therefore, the effectiveness of eliminating the neutral current is strongly dependent on the unknown system impedance, and the reduction rate may not be satisfactory in an installation location that is far from the load. Three-phase four-wire active power filters employing a four-leg inverter [6], [7] or a three-leg inverter with [8], [9] and without [10], [11] split capacitors could be used to mitigate the neutral current. These schemes are also capable of compensating line current harmonics, reactive power, and line current unbalancing. However, the schemes are complicated in control and high in cost. Single-phase series active filters [12], [13], which are connected in series with the neutral conductor, have been proposed to suppress the neutral current. These schemes are simple in configuration and control. However, analysis and control of the scheme in [12] is valid only for balanced condition, and the scheme in [13] may need to sacrifice ride-through capability by flat topping of line voltages to achieve sufficient neutral-current elimination.

A harmonic suppression scheme that is proposed in [14] employs a $\Delta - Y$ transformer, along with a single-phase inverter that is connected in parallel with the load. This scheme does not need a special design of the transformer unlike the passive zigzag transformer, and therefore, the magnetic could be smaller in size and weight. This is because the single-phase pulsewidth modulation (PWM) inverter is operated to help the zero-sequence neutral harmonics flow through the transformer back to the load. The effectiveness of eliminating the neutral current does not depend on the system impedance, and reduction rate is higher than 90% in any installation location.

This paper presents analysis and development of a hybrid neutral harmonic suppressor, which was introduced in [15], that employs a zigzag transformer that is connected in parallel with the load and a single-phase inverter that is connected in series with the neutral conductor. The rectifier part of the neutral harmonic suppressor has been removed by controlling the dc capacitor voltage. In addition to the aforementioned advantages of the scheme that is proposed in [14], which are smaller magnetic and higher reduction rate without regard to the installation location, the proposed scheme demonstrates significant reduction in the required voltampere rating of the inverter due to

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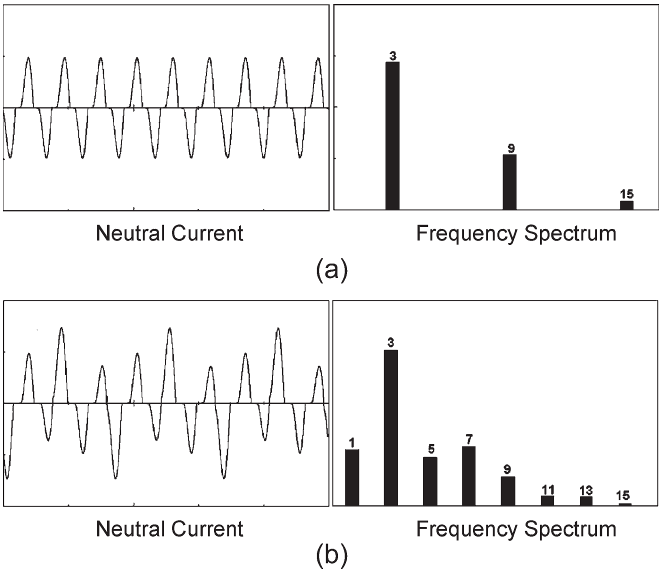

Fig. 1. Neutral-current waveform and frequency spectrum. (a) Balanced load condition. (b) Unbalanced load condition.

the series connection of the inverter. Furthermore, the proposed scheme is shown to have good compensation characteristics with both harmonic current–source loads (inductive loads) and harmonic voltage–source loads (capacitive loads). A new control method is provided such that only the harmonics in the neutral current are suppressed, while the fundamental current due to unbalanced loading remains unaffected by operation of the proposed hybrid filter.

II. PROPOSED SCHEME

A. Operating Principles

In three-phase four-wire systems, neutral current is the algebraic sum of three phase currents. Three phase currents with balanced and linear loads sum to zero; thus, there is no neutral current in this case. However, nonlinear loads such as power supplies and rectifiers have phase currents that are not sinusoidal. As shown in (1)–(4), the algebraic sum of three balanced and nonsinusoidal phase currents does not sum to zero, i.e.,

$$i_{\mathrm{La}} = I_1 \sin\omega t + I_3 \sin 3\omega t + I_5 \sin 5\omega t + \cdots \tag{1}$$

$$\begin{aligned} i_{\mathrm{Lb}} &= I_1 \sin(\omega t - 120^\circ) + I_3 \sin 3(\omega t - 120^\circ) \\ &\quad + I_5 \sin 5(\omega t - 120^\circ) + \cdots \end{aligned} \tag{2}$$

$$\begin{aligned} i_{\mathrm{Lc}} &= I_1 \sin(\omega t + 120^\circ) + I_3 \sin 3(\omega t + 120^\circ) \\ &\quad + I_5 \sin 5(\omega t + 120^\circ) + \cdots \end{aligned} \tag{3}$$

$$\begin{aligned} i_{\mathrm{nL}} &= 3I_3 \sin 3\omega t + 3I_9 \sin 9\omega t \\ &\quad + 3I_{15} \sin 15\omega t + \cdots . \end{aligned} \tag{4}$$

In particular, the zero-sequence triplen odd harmonics (third, ninth, fifteenth, etc.) do not cancel each other in the neutral conductor, thus resulting in excessive neutral current, as shown in Fig. 1(a).

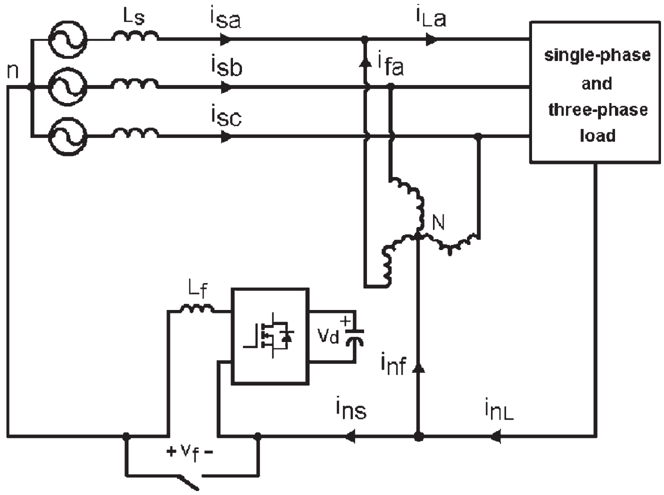

Fig. 2. Proposed hybrid filter system.

Meanwhile, neutral current resulting from unbalanced and nonlinear loads consists of not only the harmonic zero-sequence components but also the fundamental zero-sequence component, which should remain unaffected. Fig. 1(b) shows a typical neutral current waveform and its frequency spectrum with 26.8% of unbalance factor (UBF).

The voltage UBF that is defined in European standards is used in this paper as an index of the degree of unbalance. In percentage value, it is expressed as

$$\mathrm{UBF} = \frac{\text{Negative Sequence Magnitude}}{\text{Positive Sequence Magnitude}} \times 100(\%). \tag{5}$$

Fig. 2 shows the power circuit of the proposed scheme that employs a zigzag transformer that is connected in parallel with the load and a single-phase PWM inverter that is connected in series with the neutral conductor. A bypass switch is placed in parallel with the inverter and will be operated in case of inverter failure.

Let us first consider the operation with the bypass switch to be closed, i.e., with only the zigzag transformer connected to the load. All the zero-sequence currents that are generated in the load-side neutral circulate via the zigzag transformer back to the load and do not appear in the supply-side neutral if the zero-sequence impedance of the zigzag transformer is negligible compared to the source impedance. However, if it is not, the effectiveness of circulating the zero-sequence currents to the load via the zigzag transformer could not be satisfactory.

Now, the bypass switch is opened to connect the inverter in series with the neutral conductor. Proper inverter operation increases the effectiveness of circulating the zero-sequence currents to the load via the zigzag transformer. Therefore, the effectiveness does not depend on the zero-sequence impedance of the zigzag transformer and hence the installation location of the proposed filter system. Special design of the zigzag transformer for low zero-sequence impedance does not necessitate, and therefore, the size and weight of the zigzag transformer could become smaller for the proposed scheme.

Meanwhile, load-side neutral current resulting from unbalanced and nonlinear loads consists of not only the harmonic zero-sequence components but also the fundamental zero-sequence component that should remain unaffected. Therefore, only the zero-sequence harmonic currents are intended to flow via the zigzag transformer back to the load, and the zero-sequence fundamental current flows through the supply-side neutral. There are two reasons only the harmonic currents are diverted into the zigzag transformer, not allowing the fundamental current to be diverted into it.

Suppose that the loads are balanced and nonlinear. The "zero-sequence triplen odd harmonic" currents that are generated in the load-side neutral, as shown in (4), are equally divided by three, are diverted into the zigzag transformer, and cancel the triplen odd harmonic load currents, resulting in improved input current total harmonic distortion (THD) as indicated in the following. Three phase currents in the zigzag transformer become

$$\begin{aligned} i_{\mathrm{fa}} &= i_{\mathrm{fb}} \\ &= i_{\mathrm{fc}} \\ &= 1/3 \cdot i_{\mathrm{nL}} \\ &= I_3 \sin 3\omega t + I_9 \sin 9\omega t + I_{15} \sin 15\omega t + \cdots. \end{aligned} \tag{6}$$

Then, the triplen odd harmonics do not appear in the input source current, as shown in the following:

$$\begin{aligned} i_{\mathrm{Sa}} &= i_{\mathrm{La}} - i_{\mathrm{fa}} \\ &= I_1 \sin \omega t + I_5 \sin 5\omega t + I_7 \sin 7\omega t + \cdots \end{aligned} \tag{7}$$

$$\begin{aligned} i_{\mathrm{Sb}} &= i_{\mathrm{Lb}} - i_{\mathrm{fb}} \\ &= I_1 \sin(\omega t - 120^\circ) + I_5 \sin 5(\omega t - 120^\circ) \\ &\quad + I_7 \sin 7(\omega t - 120^\circ) + \cdots \end{aligned} \tag{8}$$

$$\begin{aligned} i_{\mathrm{Sc}} &= i_{\mathrm{Lc}} - i_{\mathrm{fc}} \\ &= I_1 \sin(\omega t + 120^\circ) + I_5 \sin 5(\omega t + 120^\circ) \\ &\quad + I_7 \sin 7(\omega t + 120^\circ) + \cdots. \end{aligned} \tag{9}$$

Meanwhile, if the fundamental component, which is generated on the load-side neutral under unbalanced loading, is allowed to divert into the zigzag transformer, it may be added to or subtracted from the fundamental load current, and the input current THD may become worse. Therefore, only the harmonic currents are diverted into the zigzag transformer, while the fundamental current is diverted into the inverter that is connected in series with the supply-side neutral. In the proposed scheme, the zigzag transformer could be rated considering only the harmonic currents, while the inverter could be rated considering only the fundamental current, resulting in reduced rating of both the zigzag transformer and the inverter.

This is an advantage over the scheme [14], in which all the currents are intended to divert into the zigzag transformer and to the inverter. Therefore, both the zigzag transformer and the inverter should be rated considering the harmonic currents as well as the fundamental current.

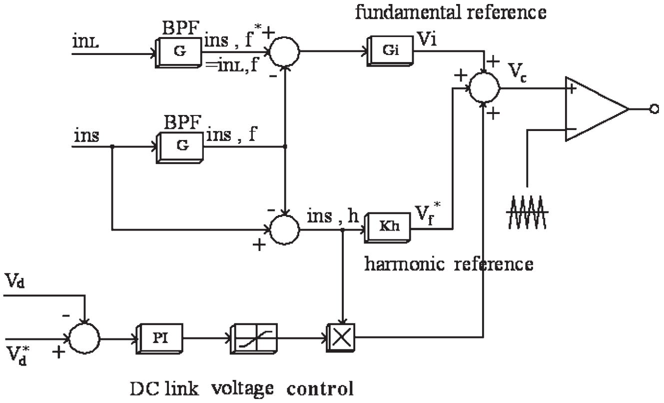

Fig. 3. Control block diagram.

B. Proposed Control and Compensation Characteristics

The control block diagram for the proposed system is shown in Fig. 3. The control can be divided into the following three parts: 1) current control for the fundamental; 2) voltage control for the harmonics; and 3) dc voltage control.

1) Current Control for the Fundamental: The current control aims at forcing the zero-sequence fundamental current that is generated by the unbalanced load into flowing through the supply-side neutral. In Fig. 3, $G_i(s)$ is a compensator for current control of the fundamental. The current reference for the fundamental component is given by

$$I^*_{\mathrm{ns},f} = G \cdot I_{\mathrm{nL}}. \tag{10}$$

The compensation characteristic for the fundamental component can be given by

$$\frac{I_{\mathrm{ns},f}}{I_{\mathrm{nL},f}} = G(s) = \frac{\frac{\omega_0}{Q} s}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2} \tag{11}$$

where $G(s)$ is the transfer function of the bandpass filter, ω_o is the angular center frequency, and Q is the quality factor. The zero-sequence fundamental current that is generated on the load-side neutral under unbalanced loading is forced to flow into the supply-side neutral by this current control, which prevents the fundamental current from flowing through the zigzag transformer.

2) Voltage Control for the Harmonics: The voltage control aims at preventing the zero-sequence harmonic currents from flowing through the supply-side neutral. In Fig. 3, K_h is a gain for voltage control of the harmonics.

a) Harmonic current–source load: The zero-sequence equivalent circuit for a pure harmonic current–source load i_{nL} is shown in Fig. 4 [17]. Here, Z_S is the source impedance, and Z_Z is the zero-sequence impedance of the zigzag transformer. The reference inverter output voltage for the harmonics is given by

$$V^*_f = K_h \cdot (1 - G) \cdot I_{\mathrm{ns}} = K_h \cdot I_{\mathrm{ns},h}. \tag{12}$$

If the harmonic equivalent resistance is K, the actual inverter output voltage can be expressed as

$$V_f = K \cdot I_{\mathrm{ns},h}. \tag{13}$$

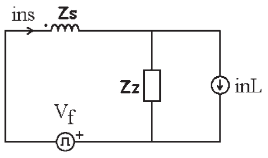

Fig. 4. Zero-sequence equivalent circuit with a pure harmonic current–source load.

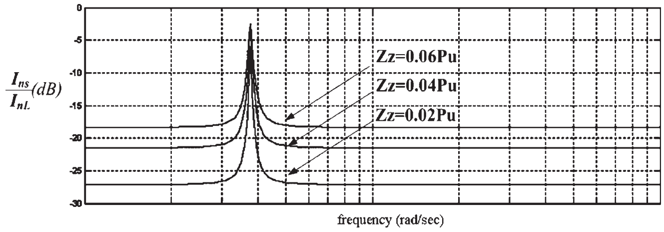

Fig. 5. Compensation characteristics of Fig. 4 ($K = 2.5$ p.u., Zs $= 0.02$ p.u., and $Q = 6$).

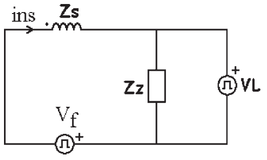

Fig. 6. Zero-sequence equivalent circuit with a pure harmonic voltage–source load.

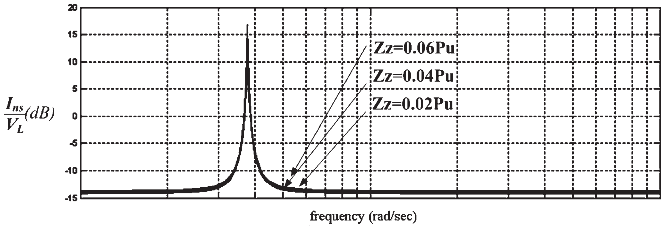

Fig. 7. Compensation characteristics of Fig. 6 ($K = 2.92$ p.u., Zz $=$ 0.02 p.u., and $Q = 6$).

The inverter is controlled in such a way as to act as a resistor with high resistance of $K[\Omega]$ for harmonic frequencies and to present zero impedance for the fundamental frequency harmonic equivalent resistance [18].

The harmonic equivalent resistance K in the single-phase full-bridge inverter can be defined by

$$K = K_h \cdot \frac{1}{A_T} \cdot V_d \tag{14}$$

where A_T is the peak amplitude of the triangular signal, and the inverter dc voltage is V_d. Then, the supply-side neutral current can be expressed from Fig. 3 as

$$I_{\text{ns}} = \frac{Z_z}{Z_s + Z_z + K(1-G)} \cdot I_{\text{nL}}. \tag{15}$$

The required operating condition of the PWM inverter in order to suppress the harmonic currents on the supply-side neutral is $K \gg Z_Z$. Fig. 5 shows the harmonic compensation characteristics of the supply-side neutral current with respect to the harmonic current–source load in case of $Z_Z = 0.02$ p.u., $Z_Z = 0.04$ p.u., and $Z_Z = 0.06$ p.u.. The system parameters for the example calculation are assumed to be $V_{\text{PU}} = 220$ V, $P_{\text{PU}} = 16.6$ kVA, $Z_{\text{PU}} = 2.92\ \Omega$, and $Z_S = 0.02_{\text{PU}}$ ($0.058\ \Omega$ and $L_S = 0.15$ mH).

Note that the magnitude gain at harmonic frequencies is sufficiently low even with considerably large zero-sequence impedances of the zigzag transformer, so that the zero-sequence harmonics that are generated on the load-side neutral are suppressed on the supply-side neutral.

b) Harmonic voltage–source load: The harmonic zero-sequence equivalent circuit for a pure harmonic voltage–source load V_L can be shown in Fig. 6. Then, the supply-side neutral current can be expressed from Fig. 6 as

$$I_{\text{ns}} = \frac{1}{Z_z + K \cdot (1-G)} \cdot V_L. \tag{16}$$

The required operating condition of the PWM inverter in order to suppress the harmonic currents on the supply-side neutral is $K \gg 1$ p.u., or Z_S is large. Fig. 7 shows the harmonic compensation characteristics of the supply-side neutral current with respect to the harmonic voltage–source load in case of $Z_S = 0.02$ p.u., $Z_S = 0.04$ p.u., and $Z_S = 0.06$ p.u. This illustrates that the zero-sequence harmonic currents that are generated from the harmonic voltage–source load are well suppressed on the supply-side neutral, not depending on the source impedance.

3) DC Voltage Control: In the proposed scheme, it is not necessary to supply the real power from the zigzag transformer or another three-phase supply for the inverter since the dc capacitor voltage can be produced by inverse energy in the neutral, i.e., by controlling the dc voltage. As shown in Fig. 3, the voltage error between the measured and the reference is sent to a proportional–integral controller, and the output is multiplied by the harmonic component of the supply-side neutral current to obtain the harmonic reference, which draws harmonic real power from the neutral for dc voltage regulation.

Under balanced loading, the inverter output voltage V_f and current i_{ns} become zero since there will be no fundamental current on the load-side neutral in theory, and therefore, the real power that is drawn by the inverter is zero. However, in practice, there will be a small amount of harmonic currents on the supply-side neutral, which were not diverted into the zigzag transformer, resulting in nonzero real power that is drawn by the inverter.

Furthermore, under unbalanced loading, there will be fundamental current both on the supply-side and load-side neutral. The inverter output current has only the fundamental, and the inverter output voltage has all the harmonics, except the fundamental. Therefore, the real power should be zero in theory. However, in practice, there will be some amount of harmonics in the inverter output current, and the inverter output voltage has a small magnitude of the fundamental. This also results in nonzero real power. Hence, owing to this nonideal operation, the inverter could draw a small amount of real power including the real power due to components' power losses in the inverter.

The dc capacitor voltage should be maintained at a desired value for proper inverter operation. The capacitance should

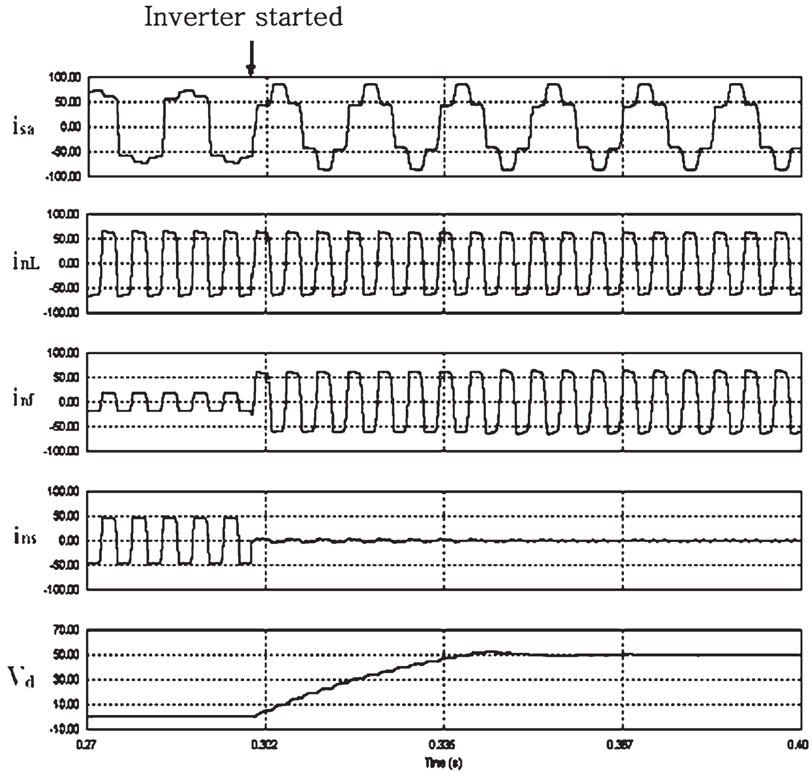

Fig. 8. Simulated waveforms for balanced harmonic current–source load.

be designed not too high, so that the voltage control can be performed with a small amount of harmonic currents. If the harmonic currents are so low that proper dc voltage control cannot be maintained, the inverter will be deactivated by closing the bypass switch.

In the proposed inverter, the required dc capacitor voltage is shown to be as low as 30 V in the 220-$V_{\rm LL}$ system, and therefore, low-cost high-efficiency metal–oxide–semiconductor field-effect transistors with smaller $R_{DS({\rm ON})}$ can be employed as a switching device.

Very low magnitude of the fundamental and harmonic currents means that the loads are very light, or linear and balanced. For both cases, the filter inverter does not need to be activated; therefore, if the magnitude of the fundamental and harmonic currents goes below some specified level, the bypass switch across the inverter output is closed, and the inverter will be deactivated. After the deactivation, if the magnitude of the fundamental and harmonic currents goes above some other specified level, the bypass switch is opened, and the dc voltage will gradually build up (see Figs. 8 and 9 in Section II-C).

C. Simulation

Fig. 8 shows the simulated waveforms of the proposed scheme for balanced harmonic current–source load. After the inverter starts to operate, the supply-side neutral current $i_{\rm ns}$ becomes nearly zero since the zero-sequence triplen harmonics in the load-side neutral flow through the zigzag transformer and do not appear on the supply-side neutral conductor. The dc capacitor voltage is gradually increased and well regulated at a designed value. It can be seen that all the triplen harmonics are suppressed in source current $i_{\rm Sa}$ since the zero-sequence triplen harmonics that are injected into the zigzag transformer cancel the zero-sequence triplen harmonic in the load phase current as well.

Fig. 9 shows the simulated waveforms of the proposed scheme for unbalanced harmonic voltage–source load. Before the inverter is started, the zero-sequence currents are generated under unbalanced loading flow not only into the zigzag transformer but also into the supply-side neutral.

After the inverter is started, only the fundamental zero-sequence current flows into supply-side neutral, and the harmonic zero-sequence currents flow through the zigzag transformer.

D. Kilovoltampere Rating of the Inverter and Zigzag Transformer

The kilovoltampere rating of the inverter switches is calculated as the product of the peak current and peak voltage. The peak current of the inverter switch can be obtained by considering only the fundamental zero-sequence of the load neutral current due to the unbalanced loading. Therefore, the current rating of the inverter switch of the proposed scheme is smaller than that of the scheme [14], where all the harmonic currents always flow through the inverter switches. The peak voltage rating of the inverter switch is equal to the dc capacitor voltage, which is determined by the inductance of filter inductor L_f and the wave shape of the inverter output current [16]. The required dc voltage of the inverter is also smaller than that of the scheme [14] since the proposed inverter needs to shape only the fundamental current. The kilovoltampere rating of the zigzag

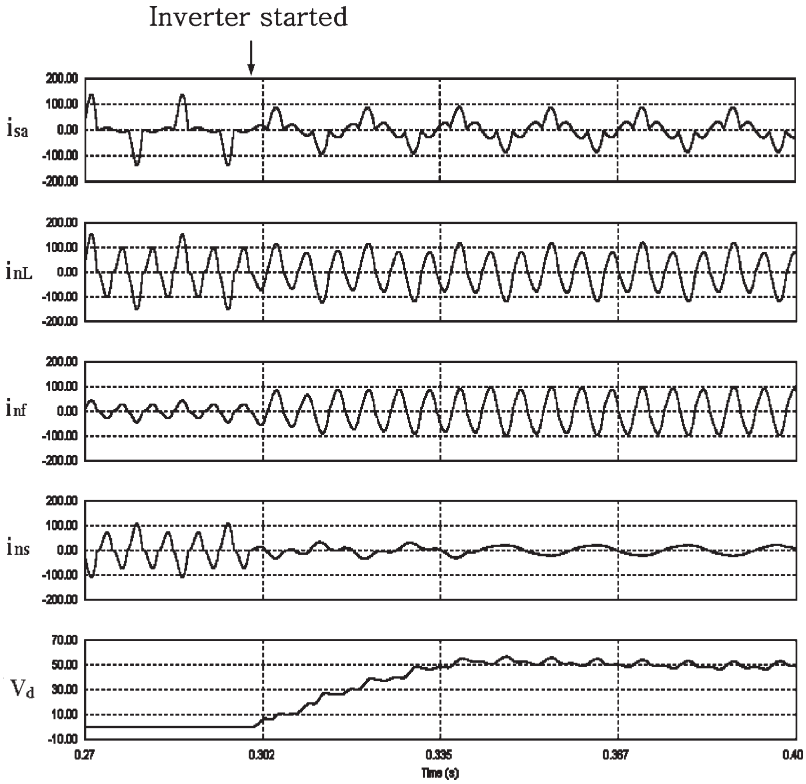

Fig. 9. Simulated waveforms for unbalanced harmonic voltage–source load.

TABLE I
FUNDAMENTAL LOAD PHASE CURRENTS FOR SPECIFIED UNBALANCED FACTORS (IN PER UNIT)

UBF	ILa,1	ILb,1	ILc,1
Balanced	1∠0	1∠-120	1∠120
10%	1∠0	0.83∠-120	1.17∠120
30%	1∠0	0.48∠-120	1.52∠120
50%	1∠0	0.13∠-120	1.87∠120

TABLE II
REQUIRED VOLTAMPERE RATING OF THE INVERTER AND TRANSFORMER

UBF	Conventional system		Proposed system	
	Inverter	Transformer	Inverter	Transformer
Balanced	1	1	0	1
10%	1.05	1.02	0.04	0.99
30%	1.27	1.11	0.11	0.94
50%	1.62	1.32	0.17	0.85

transformer is calculated as the product of the rms voltage and the rms current that is associated with each of its winding.

From many possible combinations of the three-phase load phase currents, several sets of three-phase load currents with some specified UBFs are chosen and listed in Table I for kilovoltampere rating calculation. The load phase currents are assumed to have typical waveforms like waveform i_{Sa} in Fig. 9 before the inverter is started. The inverter and the zigzag transformer kilovoltampere ratings of the proposed scheme and the conventional scheme have been calculated, and the comparative results are shown in Table II, respectively, where the voltampere ratings of the inverter and zigzag transformer are normalized with respect to the values of the conventional scheme. It should be noted that the required voltampere rating of the proposed scheme is much smaller than that of the conventional one.

III. EXPERIMENT RESULT

To demonstrate the validity of the proposed approach, the experiments have been performed with both harmonic voltage–source load and harmonic current–source load under certain conditions.

- The supply is 220 V_{LL} 60 Hz, with $Z_s = 0.35$ mH.
- The H-bridge PWM inverter is operated at $f_{\mathrm{sw}} = 20$ kHz, with a filter inductor of $L_f = 2$ mH.
- Kilowatt harmonic current–source load: Three single-phase diode rectifiers are connected between each line and neutral. Each rectifier has an R–L load of a 50-Ω resistor and a 10-mH inductor.
- Harmonic voltage–source load of 50 kVA: A total of 18 sets of switched-mode power supplies (SMPSs) has been used. Each SMPS has ratings of 220-V ac input, 48-V dc output, and 1.5-kW output power. A resistor of 1.6 Ω was used as a load for each SMPS. Six sets of SMPSs, which are connected in parallel, form a line-to-neutral load.

Fig. 10 shows the experimental waveforms on a three-phase balanced harmonic current–source load. The load-side neutral current i_{nL} contains the harmonic zero-sequence components, and the supply-side neutral current is nearly zero.

Fig. 11 shows the experimental waveforms on a three-phase unbalanced harmonic voltage–source load. The load-side neutral current i_{nL} contains not only the harmonic

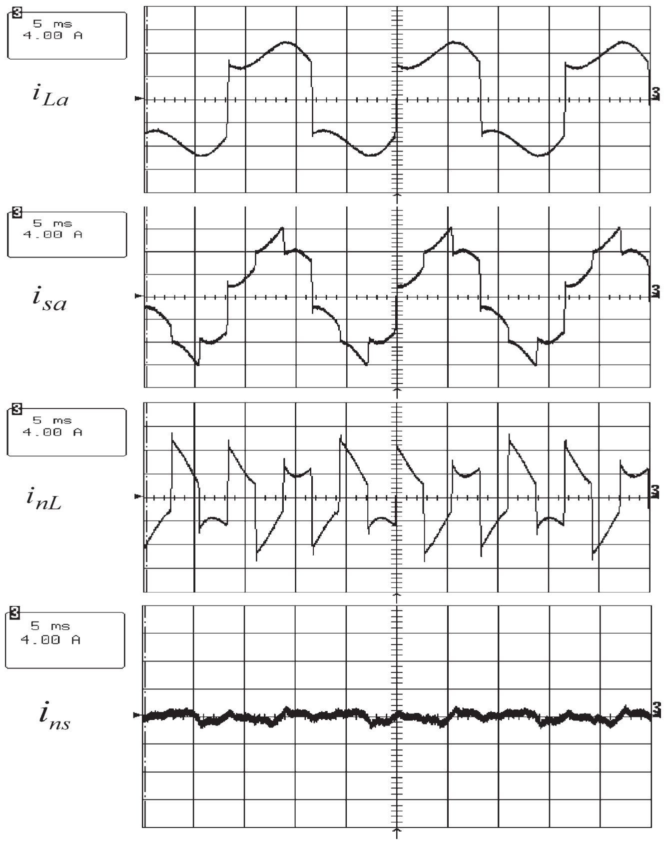

Fig. 10. Experimental waveforms for balanced harmonic current–supply load.

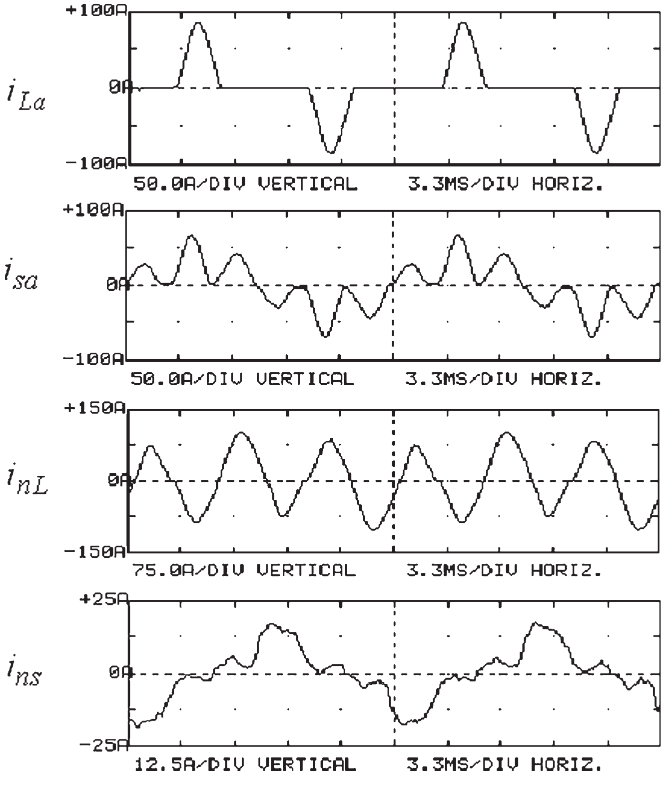

Fig. 11. Experimental waveforms for unbalanced harmonic voltage–supply load (UBF $= 30\%$).

Fig. 12. Photograph of the proposed hybrid filter for 50-kVA load.

zero-sequence components, but also the fundamental zero-sequence component, while the supply-side neutral current i_{nS} contains only the fundamental zero-sequence component. Fig. 12 shows the photograph of the prototype of the proposed neutral harmonic suppressor for 50-kVA load.

IV. CONCLUSION

In this paper, a hybrid filter is proposed to suppress neutral-current harmonics in three-phaFse four-wire electrical distribution systems. The proposed filter has advantages over the conventional schemes.

- The proposed filter demonstrates good compensation characteristics with inductive loads as well as capacitive loads.
- The voltampere rating of the inverter is significantly reduced compared to the conventional scheme that is proposed in [14].
- Under unbalanced loading, only the harmonics are suppressed, while the fundamental remains unaffected.
- The effectiveness of suppressing neutral current is over 90% without the flat-topping effect of line voltages [13]. This also does not depend on the system impedance and/or the installation location.
- The size and weight of the zigzag transformer in the proposed scheme is significantly reduced compared to that in [3]–[5].

Operating principles and control strategy along with compensation characteristics have been in detailed. The experimental results on a prototype validate the proposed control approach.

REFERENCES

[1] T. M. Gruzs, “Power system problems from high harmonic neutral current,” *Comput. Technol. Rev.*, Winter 1988.

[2] D. Paraiso, E. Ngandui, M. de Montigny, and P. Sicard, “Characterization of neutral and line current harmonics in three-phase computer power systems,” in *Proc. IEEE IECON*, 2005, pp. 946–951.

[3] P. P. Khera, “Application of zigzag transformers for reducing harmonics in the neutral conductor of low voltage distribution system,” in *Proc. IEEE IAS Conf. Rec*, pp. 1092–1990.

[4] H.-L. Jou, J.-C. Wu, K.-D. Wu, W.-J. Chiang, and Y.-H. Chen, "Analysis of zig-zag transformer applying in the three-phase four-wire distribution power system," *IEEE Trans. Power Del.*, vol. 20, no. 2, pp. 1168–1173, Apr. 2005.

[5] F. N. Belchior, J. F. V. Ferreira, J. C. Oliveira, R. Apolonio, and A. B. Vasconcellos, "Three-phase electromagnetic filter for zero-sequence harmonics," *IEEE Trans. Magn.*, vol. 42, no. 9, pp. 2201–2207, Sep. 2006.

[6] S. Jain, P. Agarwal, and H. O. Gupta, "Neutral current compensation and load balancing with fuzzy logic controlled active power filter," in *Proc. IEEE ISIE Conf. Rec*, pp. 1311–1316.

[7] L. G. Franquelo, M. A. M. Prats, R. C. Portillo, J. I. L. Galvan, M. A. Perales, J. M. Carrasco, E. G. Diez, and J. L. M. Jimenez, "Three-dimensional space-vector modulation algorithm for four-leg multilevel converters using abc coordinates," *IEEE Trans. Ind. Electron.*, vol. 53, no. 2, pp. 458–466, Apr. 2006.

[8] A. A. Valdez, G. Escobar, R. E. Torres-Olguin, and M. F. Martinez-Montejano, "A model-based controller for a three-phase four-wire shunt active filter with compensation of the neutral line current," in *Proc. IEEE CIEP*, 2006, pp. 1–6.

[9] G. Chung, "Anti-windup scheme to control DC voltage of three-phase four-wire active power filter," *Trans. KIPE*, vol. 8, no. 2, pp. 128–136, Apr. 2003. (in Korean).

[10] H. Kim, "Instantaneous power compensation theory in three-phase four-wire systems," *Trans. KIPE*, vol. 11, no. 2, pp. 172–183, Apr. 2006. (in Korean).

[11] J. Kim and Y. Kim, "Three-phase four-wire series active power filter control strategy for compensation of harmonics and reactive power based on direct compensating voltage extraction method," *Trans. KIPE*, vol. 9, no. 3, pp. 213–221, Jun. 2004. (in Korean).

[12] S. Inoue, T. Shimizu, and K. Wada, "Control methods and compensation characteristics of a series active filter for a neutral conductor," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 433–440, Feb. 2007.

[13] P. T. Cheng, C. C. Hou, and Y. F. Huang, "Overload prevention," *IEEE Ind. Appl. Mag.*, vol. 10, no. 6, pp. 26–34, Nov./Dec. 2004.

[14] P. Enjeti and W. Shireen, "Analysis and design of a new active power filter to cancel neutral current harmonics in three-phase four-wire electric distribution systems," *IEEE Trans. Ind. Appl.*, vol. 30, no. 6, pp. 1565–1572, Nov./Dec. 1994.

[15] S. Choi and M. Jang, "A reduced-rating hybrid filter to suppress neutral current harmonics in three-phase four-wire systems," *IEEE Trans. Ind. Electron.*, vol. 51, no. 4, pp. 927–930, Aug. 2004.

[16] T. Thomas, K. Haddad, G. Joos, and A. Jaafari, "Design and performance of active power filters," *IEEE Ind. Appl. Mag.*, vol. 4, no. 5, pp. 38–46, Sep./Oct. 1988.

[17] F. Z. Peng, "Application issues of active power filters," *IEEE Ind. Appl. Mag.*, vol. 4, no. 5, pp. 21–30, Sep./Oct. 1998.

[18] H. Akagi, "Active and hybrid filters for power conditioning," in *Proc. IEEE ISIE Conf. Rec.*, 2000, vol. 1, pp. TU26–TU36.

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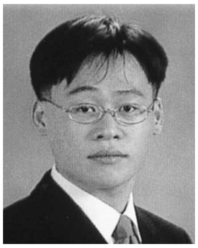

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