Letters to the Editor

A Reduced-Rating Hybrid Filter to Suppress Neutral Current Harmonics in Three-Phase Four-Wire Systems

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***Abstract*—This letter proposes a reduced-rating hybrid filter to suppress neutral current harmonics in three-phase four-wire systems. Under unbalanced loading, the proposed filter eliminates only harmonics in the neutral current while it does not affect the fundamental. The VA rating of the inverter is significantly reduced compared to the conventional one since only fundamental current due to unbalanced loading could flow through the inverter switch.**

***Index Terms*—Harmonic suppressor, neutral current, three-phase four-wire, unbalanced.**

I. INTRODUCTION

The most common loads connected to the three-phase four-wire electrical distribution system in commercial and residential buildings are nonlinear and include PC, UPS, 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. Under the worst case, the neutral current could be 1.73 times the phase current [1]. Excessive neutral currents could cause wiring failure of the neutral conductor, overloading of the distribution transformer, and a voltage drop between the neutral and the ground. Several methods have been proposed to reduce the neutral current harmonics [2]–[5]. A passive zigzag transformer arrangement which is shunt connected to the load is designed to have a low zero-sequence impedance allowing zero-sequence currents to circulate from the neutral back to the load [2]. However, the effectiveness of the method is strongly dependent upon the installation location and/or the system impedance which is usually unknown and, in general, the reduction rate is not satisfactory. Three-phase four-wire active power filters employing a four-leg inverter or three single-phase inverters demonstrate superior compensation characteristics, but the schemes are complicated in control and high in cost [3]. A cost-effective harmonic suppression scheme [4] employing a single-phase inverter along with a Δ-Y transformer in parallel with the load does not need special design of the transformer for low zero-sequence impedance unlike the passive zigzag transformer arrangement and, therefore, the magnetics could be smaller in size and weight. The effectiveness of the scheme does not depend upon the installation location and/or the system impedance, and the reduction rate is over 90% in most cases.

This letter proposes a reduced-rating hybrid filter based on the scheme in [4]. The configuration of the proposed scheme is similar to the scheme in [4] except for the connection of a single-phase inverter in series with the neutral conductor. This series connection of the inverter results in significant reduction in VA rating of the inverter due to two reasons. Firstly, only the fundamental current due to unbalanced loading could flow through the inverter switch and, therefore, the current rating of the inverter switch is reduced. Secondly, the required dc voltage of the proposed active filter inverter is also smaller than that of the scheme in [4] since the proposed inverter needs to shape only the fundamental current. Further, a control method is provided such that only harmonics in the neutral current are suppressed while the fundamental component due to unbalanced loading remains unaffected by the operation of the proposed filter.

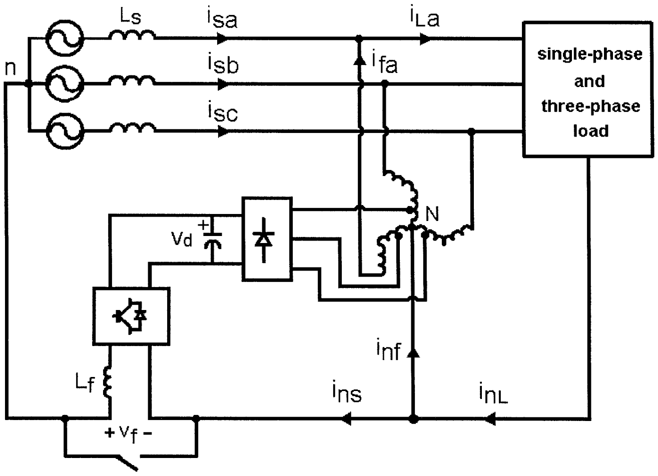

Fig. 1. Power circuit of the proposed hybrid filter system to suppress neutral current harmonics.

II. OPERATING PRINCIPLES

Fig. 1 shows the power circuit of the proposed scheme to suppress neutral current harmonics. The proposed scheme employs a single-phase pulsewidth-modulation (PWM) inverter connected in series with the neutral conductor and a zigzag transformer connected in parallel with the load. A bypass switch is placed in parallel with the inverter and will be operated in case of inverter failure.

The inverter output current i_{ns} should theoretically become zero under balanced loading since all the triplen harmonics in the load-side neutral current are forced to flow through the zigzag transformer. Under unbalanced loading the inverter output voltage has all the harmonics except the fundamental and the inverter output current has only the fundamental and, therefore, the real power should be zero in theory. However, in practice the inverter output voltage may have small magnitude of the fundamental and the inverter output current may have some harmonics, and this results in nonzero real power. Hence, the inverter should supply a small amount of real power due to this nonideal operation in addition to the real power due to the power losses of the switching devices.

The block diagram of the closed-loop control system is shown in Fig. 2(a). The load-side neutral current i_{nL} is sensed and passed through a 60-Hz bandpass filter in order to remove harmonic component. The transfer function $G(s)$ of the 60-Hz bandpass filter is assumed to be

$$G(s) = \frac{\frac{\omega_o}{Q}s}{s^2 + \frac{\omega_o}{Q}s + \omega_o^2} \tag{1}$$

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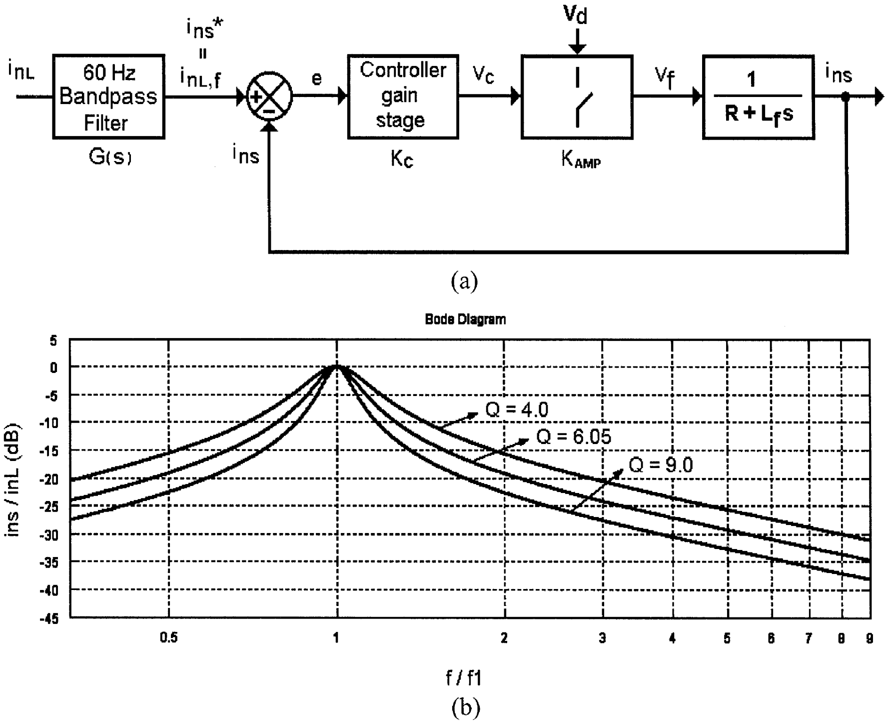

(a)

(b)

Fig. 2. Control system. (a) Block diagram. (b) Compensation characteristics.

where ω_o is the angular center frequency tuned at 60 Hz and Q is the quality factor.

The resulting neutral fundamental current $i_{nL,f}$ becomes the reference $i_{ns}*$ for current control of the inverter. The inductor L_f is selected to filter the switching ripple caused by the PWM operation of the inverter switches. Then, the closed-loop transfer function between the source-side neutral current i_{ns} and the load-side neutral current i_{nL} can be expressed as (2), shown at the bottom of the page.

Fig. 2(b) shows the compensation characteristics of the proposed hybrid filter system. As the quality factor Q increases, the passband becomes narrow. For any quality factor Q, only the fundamental component due to unbalanced loading could flow through the source side while the harmonic components are blocked from flowing into the source-side neutral conductor. This illustrates that the proposed control method prevents the zigzag transformer from overloading.

The following definition of unbalance factor is used in this paper as an index of degree of unbalance:

$$\mathrm{UBF}(\%) = \frac{\text{Negative-Sequence Magnitude}}{\text{Positive-Sequence Magnitude}} \times 100. \tag{3}$$

From many possible combinations of the three-phase load phase currents that satisfy (3), a set of three-phase load currents is chosen and listed in Table I for a specified UBF. The load phase currents are assumed to have the typical waveforms looking like i_{La} , i_{Lb}, and i_{Lc} in Fig. 3.

TABLE I
FUNDAMENTAL LOAD PHASE CURRENTS FOR SPECIFIED UNBALANCED FACTORS

UBF	$I_{La,1}$	$I_{Lb,1}$	$I_{Lc,1}$
0%	16.67∠0	16.67∠-120	16.67∠120
10%	16.67∠0	19.57∠-120	13.77∠120
30%	16.67∠0	25.37∠-120	7.97∠120
50%	16.67∠0	31.17∠-120	2.17∠120

The KVA 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 [4], 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 [6]. The required dc voltage of the inverter is also smaller than that of the scheme [4] since the proposed inverter needs to shape only the fundamental current. The inverter VA ratings

$$\frac{I_{ns}(s)}{I_{nL}(s)} = \frac{\left(\frac{1}{L_f}\frac{\omega_o}{Q}K_c \cdot K_{AMP}\right)s}{s^3 + \left(\frac{R}{L_f} + \frac{K_c \cdot K_{AMP}}{L_f} + \frac{\omega_o}{Q}\right)s^2 + \left(\frac{R}{L_f}\frac{\omega_o}{Q} + \frac{K_c \cdot K_{AMP}}{L_f}\frac{\omega_o}{Q} + \omega_o^2\right)s + \left(\frac{R}{L_f} + \frac{K_c \cdot K_{AMP}}{L_f}\right)\omega_o^2} \tag{2}$$

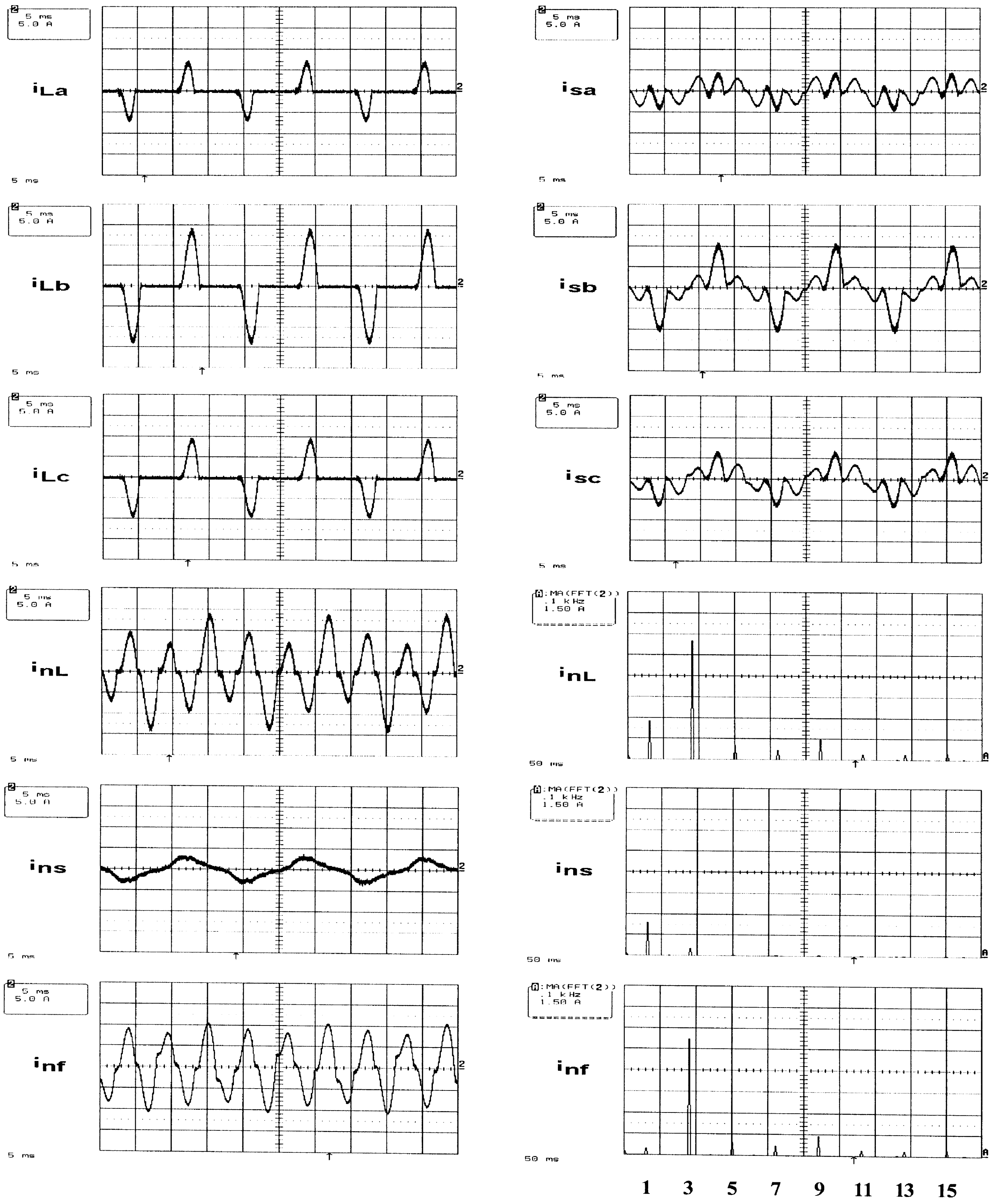

Fig. 3. Experimental waveforms (5 A/div, 5 ms/div) and frequency spectra (1.5 A/div, 0.1 kHz/div) under unbalanced loading.

of the proposed scheme and the conventional scheme have been calculated and the comparative results are shown in Table II, where the VA ratings of the inverter are normalized to be 1 pu with respect to balanced operation of the conventional scheme. It should be noted that the required VA rating of the proposed scheme is much smaller than that of the conventional one.

TABLE II
REQUIRED KVA RATING OF THE INVERTER

UBF	Conventional system Inverter (pu)	Proposed system Inverter (pu)
0%	1	0
10%	1.05	0.04
30%	1.27	0.11
50%	1.62	0.17

III. EXPERIMENT RESULTS

The system parameters used in the experiment are given as follows:

- supply—120 V (line-to-neutral, rms), 60 Hz, $L_s = 0.35$ mH;
- loads—three single-phase diode rectifiers with capacitive filter and resistive load; $C_a = C_b = C_c = 3300\ \mu$F, $R_a = 160\ \Omega$, $R_b = 60\ \Omega$, $R_c = 100\ \Omega$ for 26% of unbalanced loading;
- active filter—H-Bridge PWM inverter operated at $f_{sw} = 20$ kHz with a filter inductor $L_f = 2$ mH;
- zigzag transformer—t⇒urns ratio of 1 :0.8 : 0.2

Fig. 3 shows the experimental waveforms of each current under 26% of unbalanced loading. The load-side neutral current i_{nL} contains not only the harmonic zero-sequence components but the fundamental zero-sequence component due to the unbalanced loading among the phases. It can be noticed from the waveforms that the zero-sequence harmonics i_{nf} from the load-side neutral current i_{nL} flow through the zigzag transformer while the zero-sequence fundamental component i_{nS} caused by unbalanced loading flows through the inverter and remains unaffected. The total harmonic distortions (THDs) of the load phase currents i_{La}, i_{Lb}, and i_{Lc} are 124.9%, 105.6%, and 115.5%, respectively. The THDs of the source currents i_{sa}, i_{sb}, and i_{sc} are reduced to 113.2%, 67.0%, and 78.1%, respectively. The rms value of the inverter output voltage, which is the deviation of load neutral from ground, did not exceed 10 V which is smaller than 5% of the phase voltage of 220 V.

IV. CONCLUSION

In this letter, a reduced-rating hybrid active filter was proposed to suppress neutral current harmonics in three-phase four-wire electrical distribution systems. The compensation characteristic of the proposed scheme indicates that only harmonics in the neutral current are suppressed while the fundamental current is not affected due to unbalanced loading. The VA rating of the inverter was significantly reduced compared to the conventional one since only fundamental current due to unbalanced loading flows through the inverter switch. The experimental results on a prototype validated the proposed control approach.

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Stability Improvement of V/f-Controlled Induction Motor Drive Systems by a Dynamic Current Compensator

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***Abstract*—Stability improvement of V/f-controlled induction motor drive systems by a dynamic current compensator is proposed. The proposed method uses a dynamic current compensator to improve the stability of the V/f-controlled induction motor drive systems. This method is easy to implement and helps eliminate the oscillations causing the instability of V/f-controlled induction motor drive systems.**

***Index Terms*—Current compensator, stability improvement, V/f control.**

I. INTRODUCTION

Undesirable sustained oscillations in V/f-controlled pulsewidth-modulation (PWM) inverter-fed induction motor drive systems are often experienced in the steady state with light load. A few studies based on numerically analyzing treatment in relation to this problem have already been carried out [1], where the motor is assumed to be driven by a sinusoidal voltage source of adjustable amplitude and frequency. However, the instability of V/f-controlled induction motor drive systems may occur as the V/f control method has no means of controlling the transient operation of the drive systems [2], [3].

In this letter, stability improvement of V/f-controlled induction motor drive systems by a dynamic current compensator is proposed. The proposed method uses a dynamic current compensator to improve the stability of the V/f-controlled induction motor drive systems. This method is easy to implement and helps eliminate the oscillations causing the instability of the V/f-controlled induction motor drive systems. The theoretical analysis of the instability of the drive systems is given and the experimental result of the proposed method is also shown.

II. MATHEMATICAL MODELING

A. Stator Current Dynamic Model of the Induction Motor

Let $x = [i_{ds}\ i_{qs}\ \lambda_{dr}\ \lambda_{qr}]^T$ and $u = [v_{ds}\ v_{qs}]^T$, where i_{ds} and i_{qs} are the d-q-axes stator currents, λ_{dr} and λ_{qr} are the d–q-axes rotor fluxes, and v_{ds} and v_{qs} are the d–q-axes stator voltages in the synchronous reference frame. The field-orientation principle (FOP) is satisfied by letting $\lambda_{qr} = 0$ and $\lambda_{dr} = \lambda_r = \text{constant}$. Then, the stator current dynamic equations of the induction motor to be expressed by the $\dot{x} = Ax + Bu$ form are given by

$$\begin{aligned} \sigma L_s \frac{di_{ds}}{dt} &= -R_s i_{ds} + \omega_e \sigma L_s i_{qs} + v_{ds} \\ \sigma L_s \frac{di_{qs}}{dt} &= -R_s i_{qs} - \omega_e \sigma L_s i_{ds} - \omega_e \frac{L_m}{L_r} \lambda_{dr} + v_{qs} \end{aligned} \tag{1}$$

where

σ $= 1 - (L_m^2/L_s L_r)$;
L_s, L_r, L_m stator, rotor, and mutual inductances;
R_s stator resistance;
ω_e electrical angular velocity of the stator.

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