Elimination of Common-Mode Voltage in Three-Phase Sinusoidal Power Converters

Alexander L. Julian, *Member, IEEE*, Giovanna Oriti, *Member, IEEE*, and Thomas A. Lipo, *Fellow, IEEE*

***Abstract*—This paper presents an active solution to a common-mode voltage created by typical three-phase inverters. It is shown that the addition of a fourth leg to the bridge of a three-phase inverter eliminates the common-mode voltage to ground created by the modulation of the inverter. An appropriate four-phase LC filter is inserted between the inverter and the load in order to create sinusoidal output line-to-line voltage. A simple modification of the modulation strategy is implemented for the four-phase inverter to achieve a three-phase wye-output neutral-to-ground voltage which is equal to zero at all times for an ideal inverter. The modulation strategy thereby completely eliminates the common-mode potential produced by traditional modulation techniques with traditional three-phase inverter topologies.**

***Index Terms*— Common mode voltage, electromagnetic interference, four-phase inverter, modulation, pulsewidth modulation, resonant dc link.**

I. Introduction

COMMON mode current due to modulation in power converters introduces numerous problems in electrical systems. In aircraft, for example, inductively coupled currents may interfere with other systems such as sensitive avionics equipment. In industrial applications, such current can cause malfunctions of computers and control equipment. In motor drives and electrical networks, common-mode current even has the potential to cause physical damage or unwanted tripping of ground fault relays. Also, recent research has identified damage to electric machines caused by bearing currents [1]–[3]. These currents are created by the common-mode voltage applied to the machine by the inverter.

In typical three-phase power inverter drives, there exists substantial common-mode voltage between the load neutral and earth ground. As modulation frequencies increase and machine zero-sequence impedances decrease, the common-mode voltage causes larger common-mode currents, worsening electromagnetic interference (EMI) problems and potentially damaging the network or the machine.

This paper presents a power converter which realizes sinusoidal balanced three-phase-output voltage with respect to earth ground with essentially no common-mode voltage. A complete analytical model of a pulsewidth-modulated (PWM) converter is presented and used to simulate the behavior of the system. It is shown that an alternative to expensive and large high-impedance common-mode filters (such as baluns) is to appropriately reduce or even eliminate the common-mode voltage driving the common-mode current. While a somewhat related inverter topology has already been reported to contain the zero-sequence components due to unbalanced loads [4], in this paper a similar inverter topology is used to control the neutral-to-ground voltage for the purpose of eliminating conducted EMI.

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A. L. Julian and G. Oriti are with the United Technologies Research Center, East Hartford, CT 06108 USA.

T. A. Lipo is with the University of Wisconsin, Madison, Madison, WI 53706 USA.

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II. The Four-Leg Converter

The topology proposed in this paper is drawn in Fig. 1 showing the addition of a fourth leg to the bridge of a three-phase inverter together with a second-order filter and a three-phase RL load (plain-line circuit). It can be noted that a capacitor connected between the load neutral and ground is included in the model. This capacitor represents the parasitic capacitive coupling that typically exists between the load and ground. For example, in a motor there is substantial capacitive coupling between the motor windings and the motor case, which is typically grounded. The parasitic coupling represented by the capacitor C_g in Fig. 1 is the path through which the common-mode current flows, creating the problems described in the previous section.

It will be shown that for balanced loads the fourth leg of the inverter and the filter components can be derated with respect to the other three phases.

A simple modification of the modulation strategy can be implemented for the four-phase inverter to achieve an output neutral voltage which is equal to zero at all times, thereby eliminating common-mode potential produced by traditional modulation techniques.

The necessary condition to achieve zero common-mode voltage is

$$V_1 + V_2 + V_3 + V_4 = 0. \tag{1}$$

It can be noted that (1) places a constraint on the allowable switch states, since it implies that two top switches and two bottom switches must be on at all times in the four inverter legs. As a consequence, the zero state $(S1 = S2 = S3)$, typically used by three-phase inverter modulators, is not allowed. In the presence of a load, the common-mode voltage can then be eliminated with any modulation strategy (i.e., PWM, hysteresis, space vector, and PDM) provided that the modulation constraint in (1) is satisfied and the three-phase-output load is balanced.

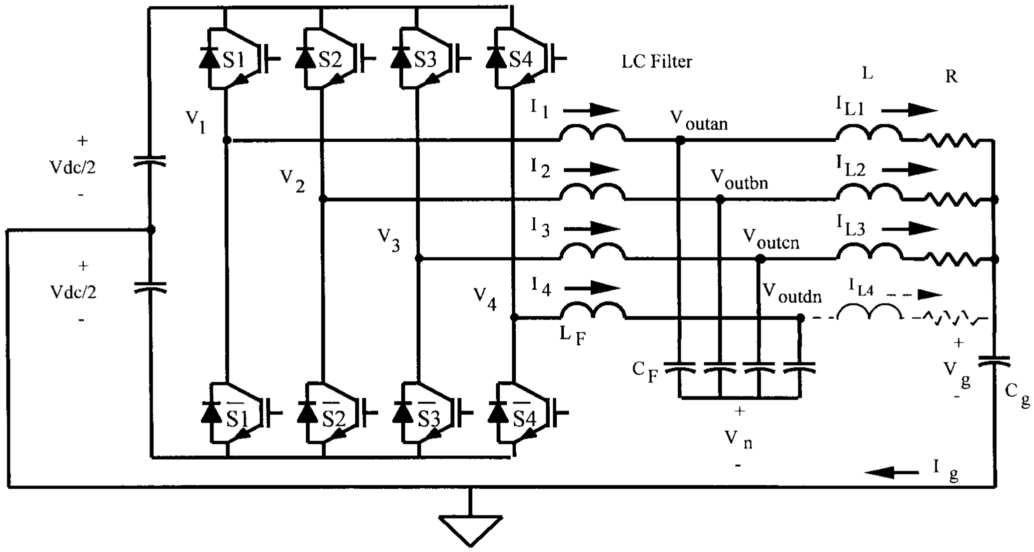

Fig. 1. Four-leg inverter with second-order filter and motor load.

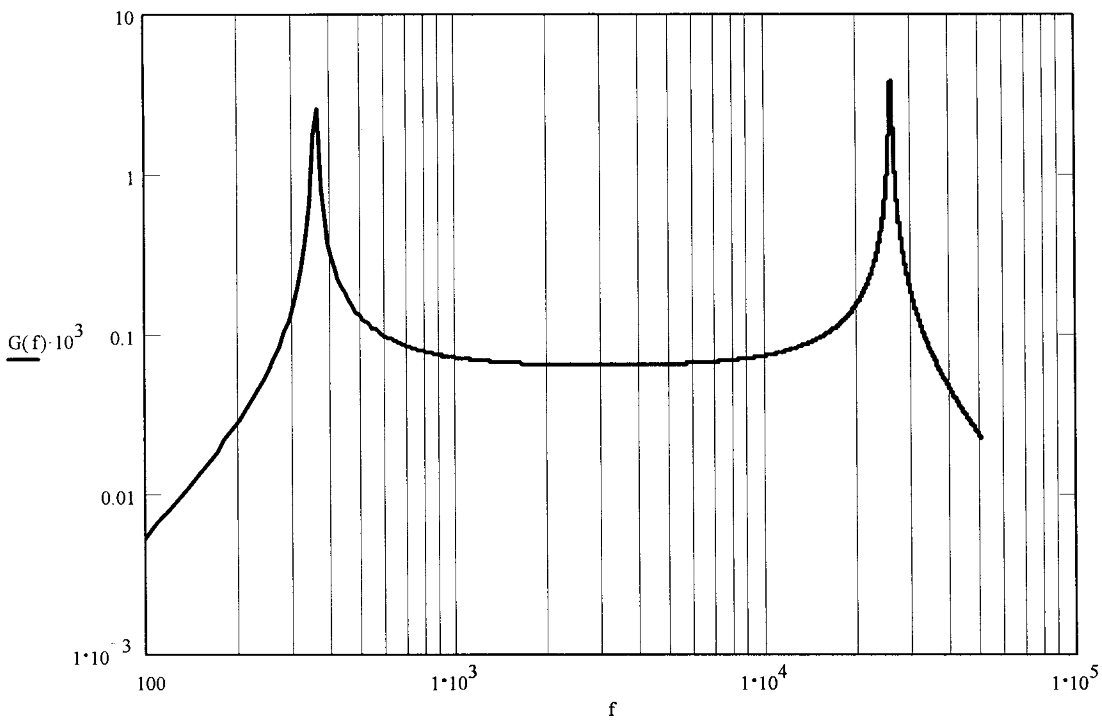

Fig. 2. Transfer function V_n/V_4 versus frequency.

III. Theoretical Proof

In order to simplify the analysis let us assume that the four-leg inverter drives a four-phase balanced load. For this analysis, we will refer to the schematics shown in Fig. 1 including the RL load on the fourth phase, drawn with dotted lines. For this four-phase system the following differential equations apply:

$$V_1 = sL_F I_1 + sLI_{L1} + RI_{L1} + V_g \quad (2)$$
$$V_2 = sL_F I_2 + sLI_{L2} + RI_{L2} + V_g \quad (3)$$
$$V_3 = sL_F I_3 + sLI_{L3} + RI_{L3} + V_g \quad (4)$$
$$V_4 = sL_F I_4 + sLI_{L4} + RI_{L4} + V_g \quad (5)$$

where s represents the differential operator and the ground voltage is given by

$$V_g = \frac{I_g}{sC_g}. \quad (6)$$

The following current nodal equations can also be derived:

$$I_{L1} + I_{L2} + I_{L3} + I_{L4} = I_1 + I_2 + I_3 + I_4 = I_g. \quad (7)$$

Summing (2)–(5) and substituting (6) and (7) yields

$$V_1 + V_2 + V_3 + V_4 = 0 = \left(sL_F + sL + R + \frac{4}{sC_g}\right) I_g. \quad (8)$$

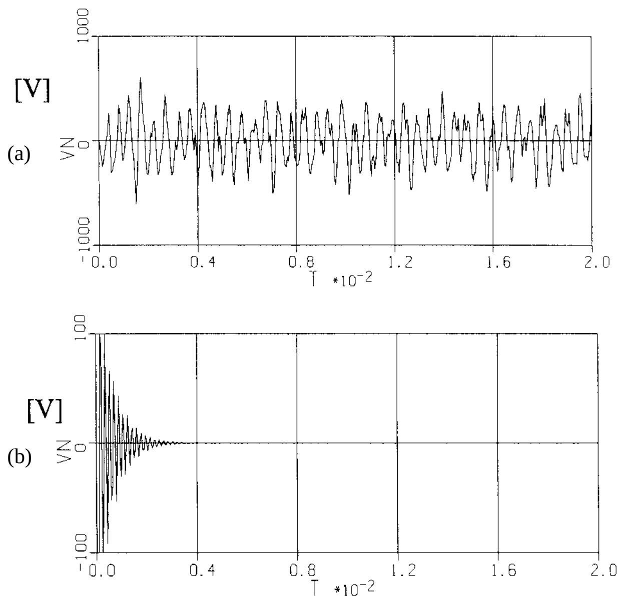

Fig. 3. Simulated V_n for a (a) three-leg and (b) four-leg converter.

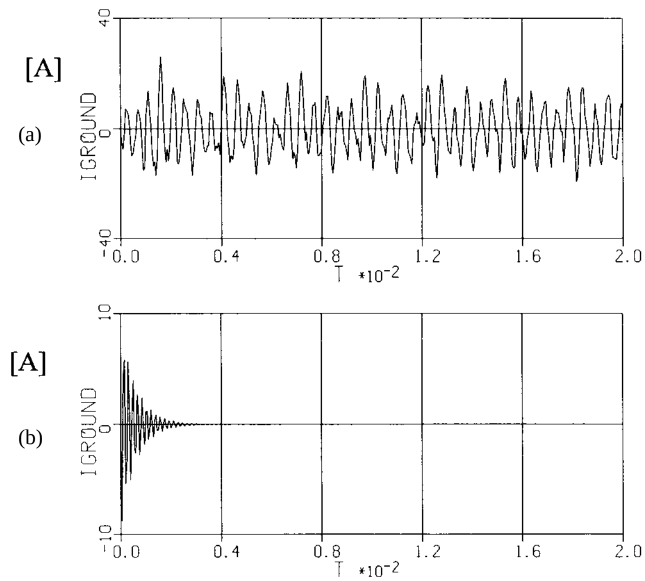

Fig. 4. Simulated ground current for a (a) three-phase and (b) four-phase converter (lower).

The only possible solution to (8) is $I_g = 0$, which when substituted into (6) yields $V_g = 0$. Given this result, it is also possible to demonstrate that the filter neutral voltage, V_n is zero.

In practical systems it is not convenient to create a four-phase load, therefore the four-leg system shown in Fig. 1 seems more appropriate. The small unbalancing created in this way does not have a significant impact on the common-mode voltage, as is proved in the following analysis.

When the assumption of a four-phase balanced load is relaxed (exclude the dotted-line drawing in Fig. 1), but the modulation constraint is still enforced, the filter neutral voltage transfer function can be expressed as a function of V_4

$$\frac{V_n}{V_4} = \frac{s^2 L_F + sR_F}{s^4 b_4 + s^3 b_3 + s^2 b_2 + s b_1 + b_0} \tag{9}$$

where R_F is the resistance of the filter inductance, L_F. R_F is not identified as a separate circuit element in Fig. 1.

The coefficients of this characteristic equation are shown in the Appendix. Equation (9) identifies the eigenvalues of the filter and the resonant frequencies which may exist in the filter. Fig. 2 plots the gain of (9), identifying the resonant frequencies of concern. The low gain of V_n in Fig. 2 indicates that even in the presence of an unbalanced load (three-phase load) the neutral voltage of the four-leg inverter is still very small. This preliminary result will be confirmed by computer simulations and lab measurements, which are reported in the following sections.

TABLE I
PASSIVE COMPONENTS VALUE IN THE SIMULATION

Component	Symbol in Fig. 1	Value
filter inductor	L_F	0.5 mH
filter capacitor	C_F	400 µF
load inductor	L	10 µH
load resistance	R	1Ω
ground capacitor	C_g	0.3 µF

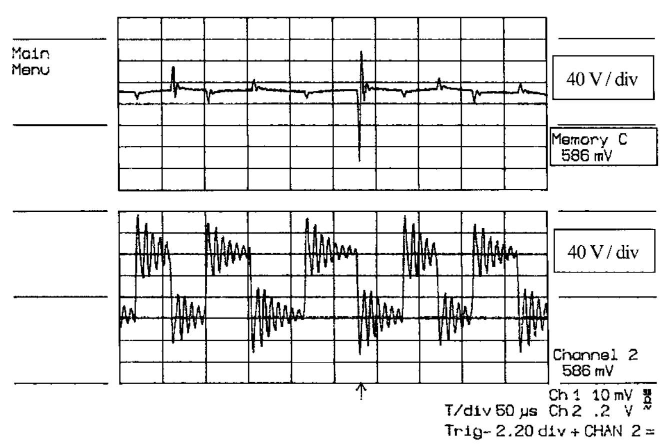

Fig. 5. Machine neutral voltage in a PWM drive with and without active filtering.

IV. SIMULATION RESULTS

A complete model of the three-phase system (Fig. 1) including the four-leg power inverter, the second-order filter and a simplified load model with capacitive coupling to ground was first simulated to demonstrate feasibility of the concept. In this section results of simulations of a PWM-controlled hard-switching converter are presented.

For the hard-switching converter a sine triangle PWM technique has been used with three carrier waves phase dis-

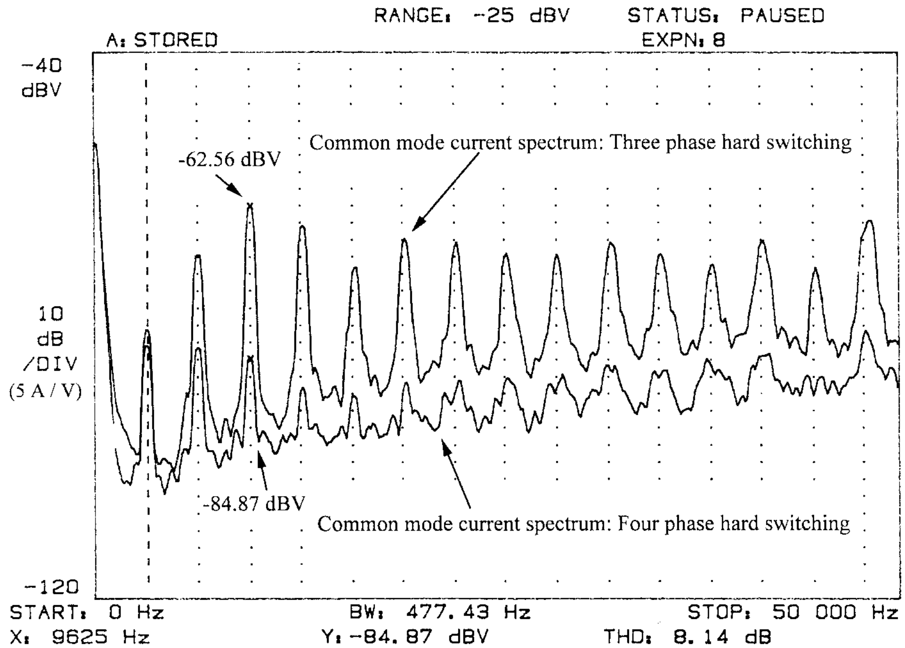

Fig. 6. Common-mode-conducted EMI in a PWM drive with and without fourth inverter pole.

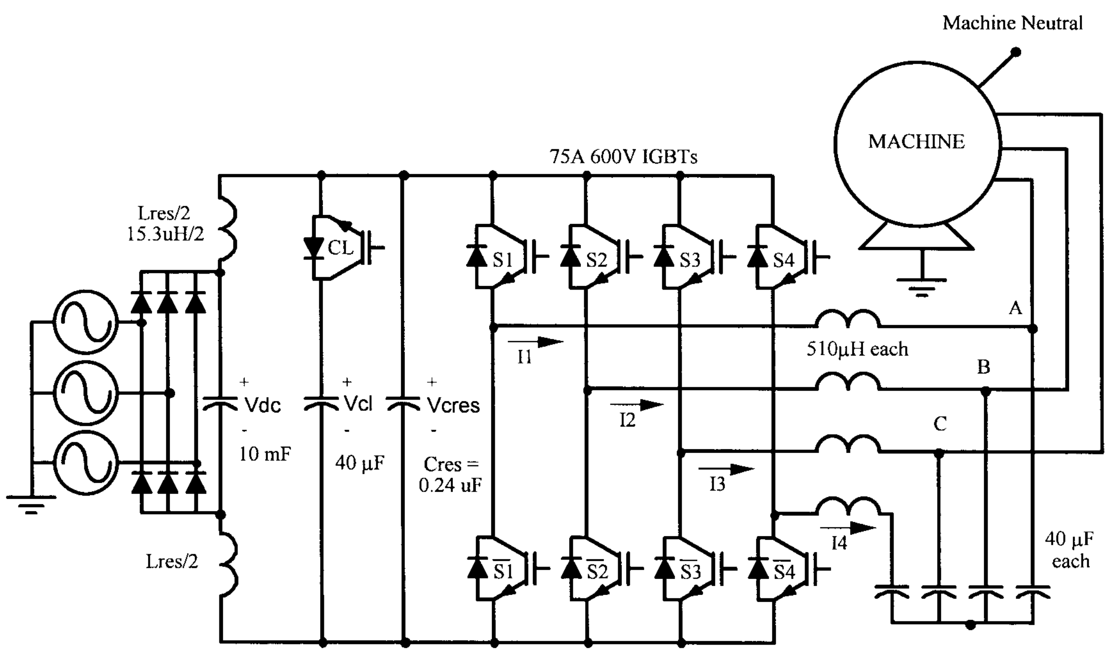

Fig. 7. Schematic of the practical RDCL four-phase converter. Channel A: 100 V/div. Channel 2: 100 V/div.

placed by 120° in order to satisfy the constraint of (1). This modification to the single carrier sine triangle modulation introduces a somewhat higher differential voltage distortion while eliminating common-mode voltage distortion and is limited to a modulation index of 0.66. The modulation index is the ratio of the triangle carrier amplitude to the reference sine wave amplitude. Beyond a 0.66 modulation index the constraint of (1) is no longer satisfied. Further studies have already shown that other modulation strategies, such as space vectors [5] can be applied to the four-phase inverter in order to reduce the common-mode voltage without limiting the modulation index. In this section, simulation results for sine-triangle PWM modulation are shown to prove that the proposed topology ideally eliminates the common-mode voltage and current.

The simulation results are shown in Figs. 3 and 4 for a typical three-leg inverter and for the proposed four-leg inverter. As can be noted in Fig. 3, the neutral voltage in the four-leg topology is zero while in the three-leg converter substantial neutral voltage exists. Fig. 4 demonstrates that the current flowing in the ground wire for a traditional three-leg inverter has been eliminated in the four-leg topology.

Table I shows the values used in the simulation for the passive components shown in Fig. 1. The dc voltage is $V_{dc} = 400$ V.

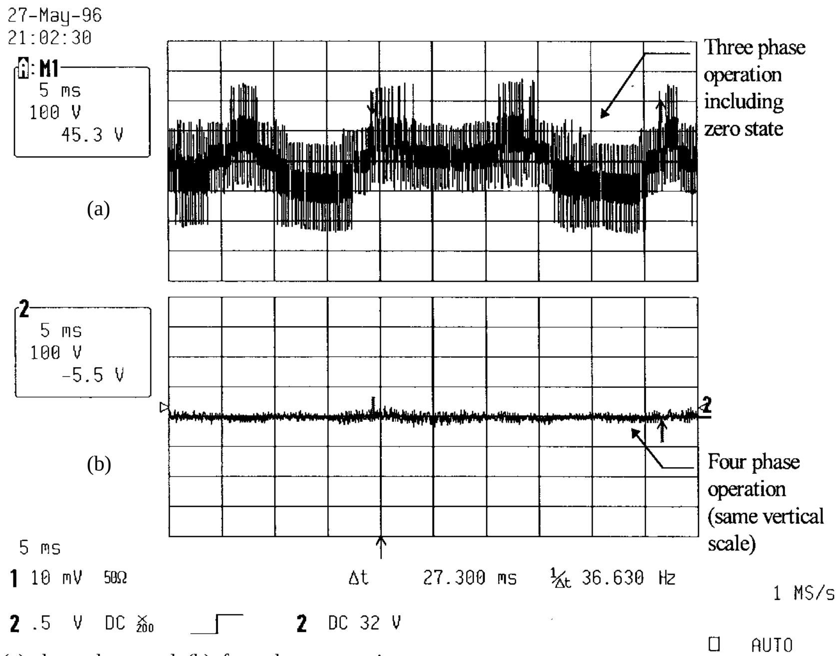

Fig. 8. Measured V_n for a (a) three-phase and (b) four-phase operation.

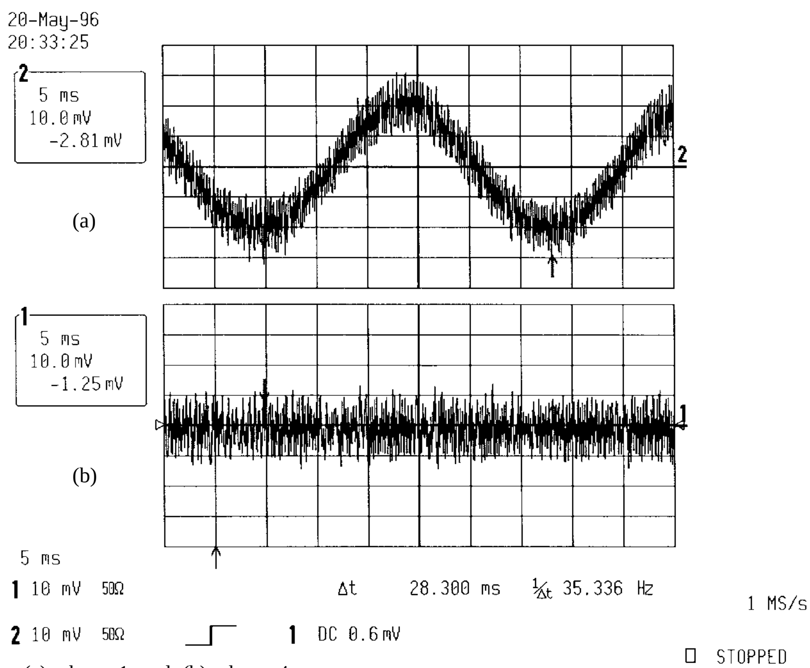

Fig. 9. Inverter phase currents: (a) phase 1 and (b) phase 4.

V. Experimental Results

The simulated circuit was built in the laboratory and tested. A 3-HP induction motor was used as load. The filter components were LF $= 800\ \mu$H and CF $= 40\ \mu$F. The modulation strategy used in the simulations was implemented with a digital signal processor (DSP). Fig. 5 shows the neutral voltage of a three-phase induction motor with respect to earth ground (identified as V_g in Fig. 1) with and without the active filter. The impact of the fourth inverter leg is dramatic and consistent with simulation results. Fig. 6 shows the spectra of the ground current of the induction machine (identified as I_g in Fig. 1) with and without the fourth leg. The first zero-sequence component of the ground current (which is the third harmonic of the modulation carrier) is reduced from -62.56 to -84.87 dBV. It should be noted that the three carriers used in this modulation strategy are phase shifted from each other by 120°. As a result, no change in the amplitude of the common-mode current at the carrier frequency (3.2 kHz) is observed in Fig. 6.

In addition to the hard-switching measurements already presented, a four-phase filter and resonant dc-link (RDCL) inverter has been built to further verify experimentally the reduction of the neutral voltage of the filter. The lab circuit used for hardware measurements is shown in Fig. 7.

Fig. 8 shows the measured motor neutral-to-ground voltage for three- and four-phase operation modes of the RDCL

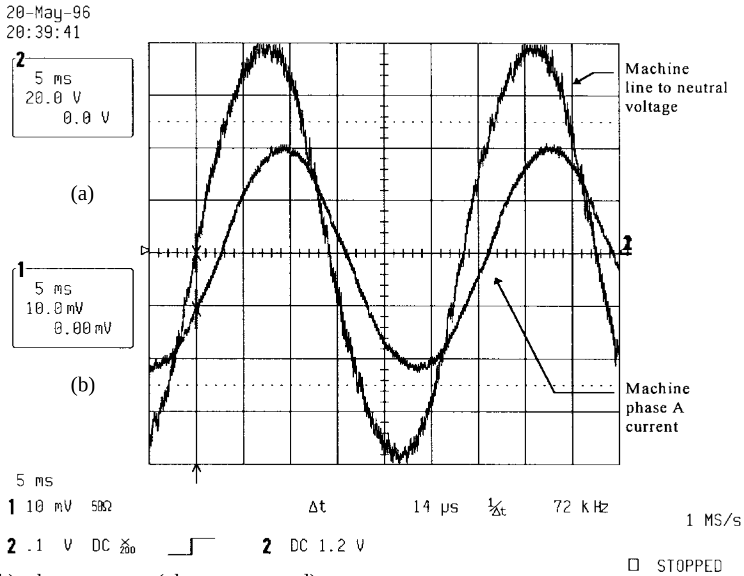

Fig. 10. (a) Motor voltage and (b) phase current (phase to neutral).

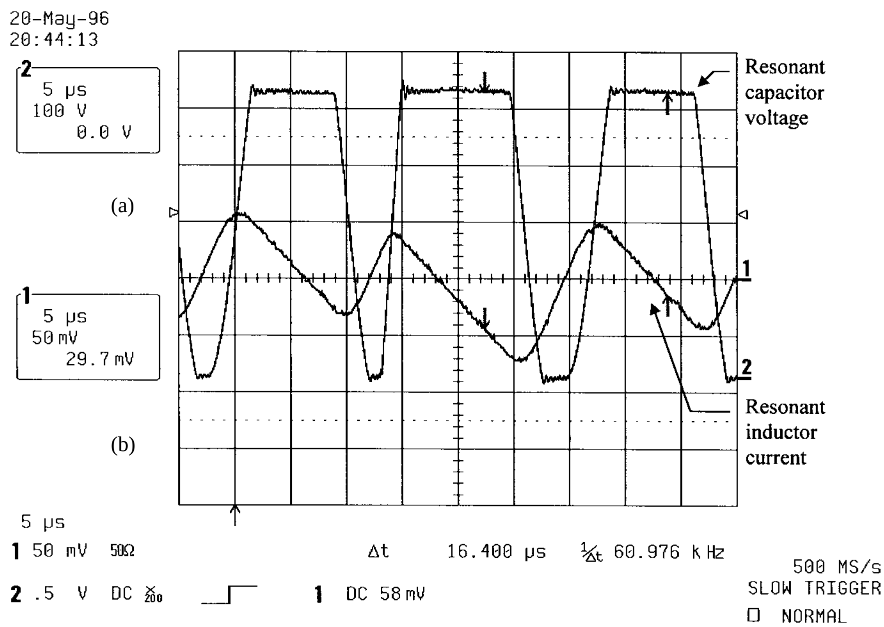

Fig. 11. (a) Resonant link voltage and (b) current in the resonant inductor.

converter. In comparing the two plots in Fig. 8, the significant difference supports the simulation results. That is, the common-mode voltage due to modulation energy is drastically reduced when the fourth pole is added to the inverter.

Fig. 9 plots the waveforms of the load currents flowing in phases 1 and 4, respectively. They are plotted in the same scale in order to highlight that the fourth leg of the inverter does not carry load current, but only ripple current. This result suggests that the power devices used in the fourth leg can be derated as much as 10:1 with respect to those used for the other three phases, thus reducing the cost of the active solution proposed.

The inverter output voltage and phase current are plotted in Fig. 10 in order to show that the differential mode performances of the converter have not been worsened. Fig. 11 shows the resonant bus voltage and the resonant inductor current of the RDCL converter.

Fig. 12 shows the average spectra of the motor neutral-to-ground voltage for the two converter topologies and provides an excellent contrast between three- and four-phase operations. Three spectra are compared in Fig. 12 for three operation modes of the inverter: three phase with typical sigma delta modulation, three phase without zero state, and four-phase operation. It can be noted that eliminating the zero state has a significant impact on the common-mode voltage spectrum, except for the resonant frequency component. This component, corresponding to 63 kHz for this RDCL inverter, is eliminated when the inverter operates with four poles.

VI. Conclusions

In this paper, a new strategy for minimizing the common-mode voltage has been presented using the concept of a fourth "pseudophase" in a three-phase system. Experimental

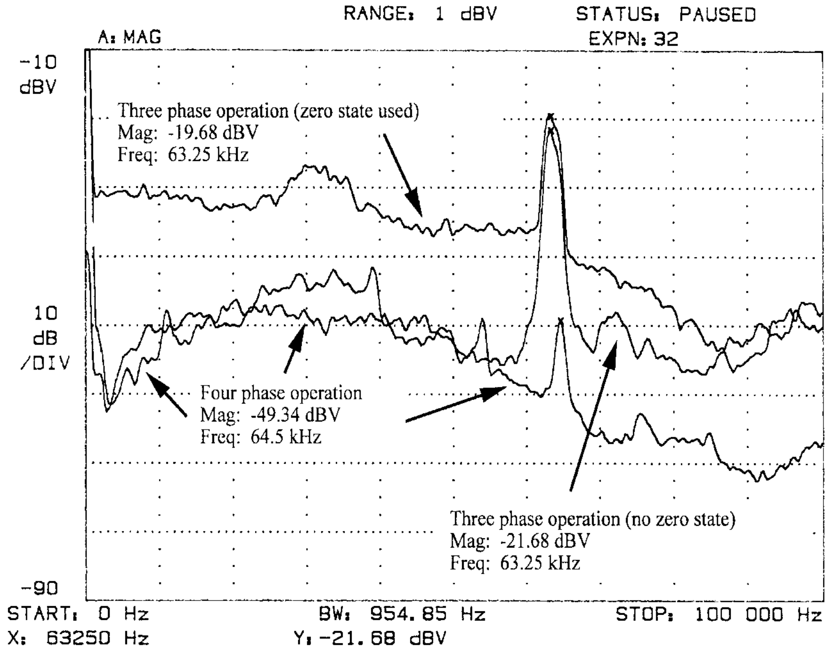

Fig. 12. Spectra of the motor neutral-to-ground voltage in the three operation modes of the ACRDCL converter.

measurements performed on a four-phase hard-switching pulse width modulated inverter and a four-phase resonant dc link (RDCL) show that the switching frequency component of the common-mode voltage is much smaller when a fourth phase is added compared to that measured in typical three-phase inverters. Actively canceling common-mode voltage is presented as an attractive alternative to passive filtering techniques to reduce common-mode-conducted EMI.

APPENDIX

By writing the differential equations of the system shown in Fig. 1 with the constraint of (1) and the assumption that the filter and load are balanced, (9) can be computed where the coefficients are

$$b_4 = 4L_F C_F L + 3C_F L_F^2 \tag{10}$$

$$b_3 = 4RL_F C_F + 4R_F C_F L + 6R_F C_F L_F \tag{11}$$

$$b_2 = 12L_F \frac{C_F}{C_g} + 4R_F C_F R + 4(L_F + L) + 3C_F R_F^2 \tag{12}$$

$$b_1 = 12R_F \frac{C_F}{C_g} + 4(R_F + R) \tag{13}$$

$$b_0 = \frac{12}{C_g}. \tag{14}$$

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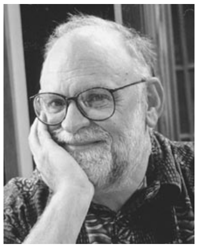
Alexander L. Julian (S'91–M'98) received the B.S.E.E. and M.S.E.E. degrees from the University of Missouri, Columbia, in 1991 and 1992, respectively, and the Ph.D. degree in electrical engineering from the University of Wisconsin, Madison, in 1998.

He was with Boeing Corporation, Soft Switching Technologies, and Eaton Corporation. He is presently a Research Engineer at United Technologies Research Center, East Hartford, CT. His research interests include solid-state power conversion and electromagnetic compatibility.

Giovanna Oriti (S'93–M'98) was born in Catania, Italy. She received the Laurea degree with honors and the Ph.D. degree, both in electrical engineering, from the University of Catania, Italy, in 1993 and 1997, respectively.

In 1992, she was a Visiting Scholar at the University of Newcastle upon Tyne, U.K. From 1996 to 1998, she was a Research Intern at the University of Wisconsin, Madison. In 1998, she joined United Technology Research Center, East Hartford, CT. Her research interests include solid-state power converters, drives, and electromagnetic compatibility.

Dr. Oriti was a recipient of the European Community ERASMUS scholarship. She is a member of the IEEE Industry Application and Power Electronics Societies.



Thomas A. Lipo (M'64–SM'71–F'87) is a native of Milwaukee, WI.

From 1969 to 1979, he was an Electrical Engineer in the Power Electronics Laboratory, Corporate Research and Development, General Electric Company, Schenectady, NY. He became Professor of Electrical Engineering at Purdue University, West Lafayette, IN, in 1979, and in 1981 he joined the University of Wisconsin, Madison, in the same capacity, where he is presently the W. W. Grainger Professor for Power Electronics and Electrical Machines.

Dr. Lipo received the Outstanding Achievement Award from the IEEE Industry Applications Society, the William E. Newell Award from the IEEE Power Electronics Society, and the 1995 Nicola Tesla IEEE Field Award from the IEEE Power Engineering Society for his work. Over the past 30 years, he has served IEEE in numerous capacities including being President of the Industry Applications Society.