Research Report

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

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Abstract –The paper describes the addition of a fourth leg to the bridge of a three phase inverter for the purpose of eliminating the common mode voltage to ground. An appropriate four phase filter is used to eliminate common mode currents due to modulation. With a suitable modulation strategy and a three phase LC filter on three legs of the inverter sinusoidal output line-to-line voltages are obtained. A simple modification of the modulation strategy is implemented for the four phase inverter to achieve a three phase star output neutral to ground voltage which is equal to zero at all times. The modulation strategy thereby completely eliminates the common mode potential produced by traditional modulation techniques with traditional inverter topologies.

I. INTRODUCTION

Common mode current due to pulse width 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 avionic 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 relays. Also, recent research has identified damage to electric machines caused by bearing currents [1,2,3]. 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 EMI problems and potentially damaging the network or the machine.

This paper presents a power inverter which realizes sinusoidal balanced three phase output voltage with respect to earth ground with essentially no common mode voltage. A complete analytical model of this 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 circuit has already been reported to contain the zero sequence components due to unbalanced loads [4], this new circuit presents, for the first time, a means to control the neutral to ground voltage for the purpose of eliminating conducted EMI.

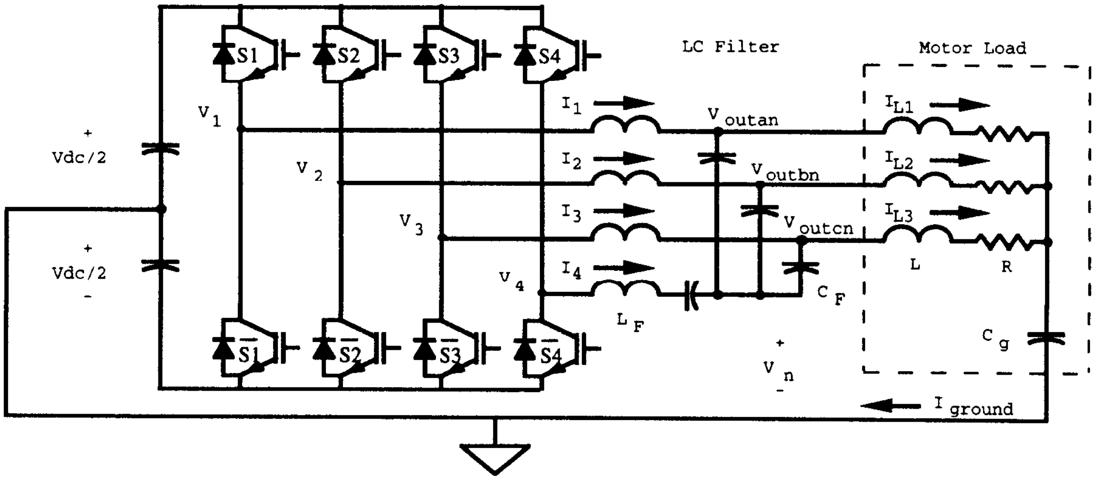

Fig. 1 - Four leg inverter with second order filter and motor load.

II. THE 4 PHASE CONVERTER

The topology proposed in this paper is shown 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 simplified high frequency motor model. The four leg power inverter together with an appropriate four phase filter is then used to eliminate common mode currents due to modulation.With an appropriate modulation strategy, a three phase LC filter on three legs of the inverter produces sinusoidal output line-to-line voltages. 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 completely 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 equation (1) places a constraint on the allowable switch states. As a consequence, the zero state (S1=S2=S3) is not allowed. In the presence of a load, common mode voltage can then be eliminated with any modulation strategy (i.e. PWM, hysteresis, space vector, PDM) provided that the modulation constraint in equation (1) is satisfied and the three phase output load is balanced.

III. THEORETICAL PROOF

In order to simplify the analysis it can be assumed that the three phase load is balanced and:

$$I_{L1} + I_{L2} + I_{L3} = 0 \tag{2}$$

Given the constraint of Equation (2) it is also true that

$$I_1 + I_2 + I_3 + I_4 = 0 \tag{3}$$

The voltage loop equations are:

$$V_1 - (V_{outan} + V_n) = L \cdot \frac{dI_1}{dt} \tag{4}$$

$$V_2 - (V_{outbn} + V_n) = L \cdot \frac{dI_2}{dt} \tag{5}$$

$$V_3 - (V_{outcn} + V_n) = L \cdot \frac{dI_3}{dt} \tag{6}$$

$$V_4 - (V_{outdn} + V_n) = L \cdot \frac{dI_4}{dt} \tag{7}$$

The current nodal equations are:

$$I_1 = C\frac{dV_{outan}}{dt} + I_{L1} \tag{8}$$

$$I_2 = C\frac{dV_{outbn}}{dt} + I_{L2} \tag{9}$$

$$I_3 = C\frac{dV_{outcn}}{dt} + I_{L3} \tag{10}$$

$$I_4 = C \cdot \frac{dV_{outdn}}{dt} \tag{11}$$

By substituting equations (8)–(11) into (3) and using (2) it can be shown that the four voltages must add up to a constant value. However at t = 0 (upon energization) the voltages in (8)–(11) are clearly zero and therefore:

$$V_{outan} + V_{outbn} + V_{outcn} + V_{outdn} = 0 \tag{12}$$

Substituting Equations (4)–(7) into (1) yields:

$$-4V_n = L\frac{d(I_1 + I_2 + I_3 + I_4)}{dt} = 0 \tag{13}$$

This result shows that the neutral voltage V_n therefore remains zero for all time.

When the assumption of equation (2) is relaxed, but the modulation constraint of equation (1) is used and the filter and the load are assumed to be balanced, then V_1, V_2 and V_3 can be eliminated and the filter neutral voltage transfer function can be expressed as a function of V_4:

$$\frac{V_n}{V_4} = \frac{s^2 L_F + sR_F}{s^4 b_4 + s^3 b_3 + s^2 b_2 + sb_1 + b_0} \tag{14}$$

The coefficients of this characteristic equation are shown in the appendix. Equation (14) identifies the eigenvalues of the filter and the resonant frequencies which may exist in the filter. Fig. 2 plots the gain of equation (14), identifying the resonant frequencies of concern. Equation (14) predicts the resonance in the fourth phase that is observed in the lab. The low gain of V_n in Fig. 2 indicates that even in the presence of common mode current (equation (2) is not zero) the neutral voltage is still very small.

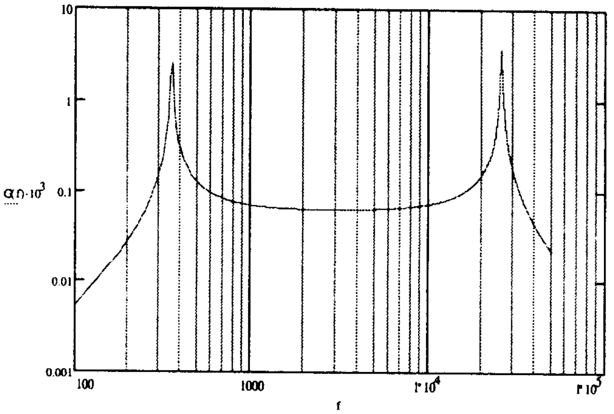

Figure 2: Transfer function V_n/V_4 vs. frequency

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 high frequency motor model with capacitive coupling to ground was first simulated to demonstrate feasibility of the concept. In this section results of simulations of a pulse width modulation (PWM) controlled hard switching converter is presented.

For the hard switching converter a sine triangle PWM technique has been used with three carrier waves phase displaced by 120° in order to satisfy the constraint of equation (1). This modification to the single carrier sine triangle modulation introduces somewhat higher differential voltage distortion while eliminating common mode voltage distortion and is limited to a modulation index of 0.66. Beyond 0.66 modulation index the constraint of equation (1) is no longer satisfied.

Simulation results are shown below in order to compare a three leg inverter with 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.

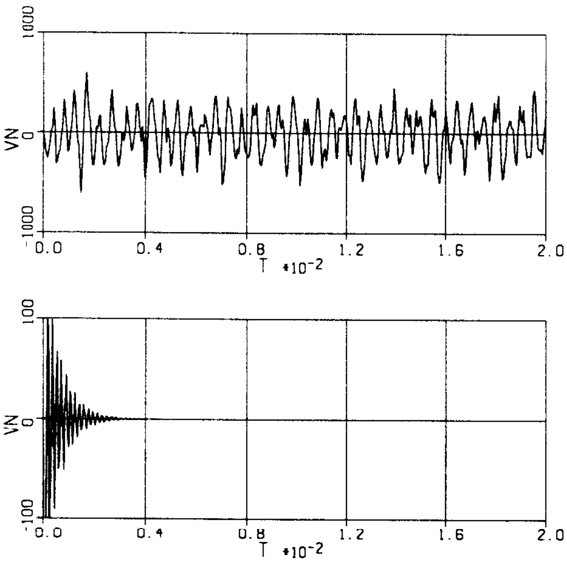

Figure 3: Simulated V_n for a 3 phase (upper) and for a 4 phase converter (lower)

V. EXPERIMENTAL RESULTS

A four phase filter and resonant DC link inverter has been built to verify experimentally the reduction of the neutral voltage of the filter. The ideal system model used for simulations suggests that the neutral voltage can be eliminated however the measured results indicate that many factors such as a non-ideal second order filter and non-ideal switching contribute to the neutral voltage. The lab circuit used for hardware measurements is shown in Fig. 5. In the lab circuit resistive loads (including 5Ω on the fourth phase) are used to provide passive damping of resonance.

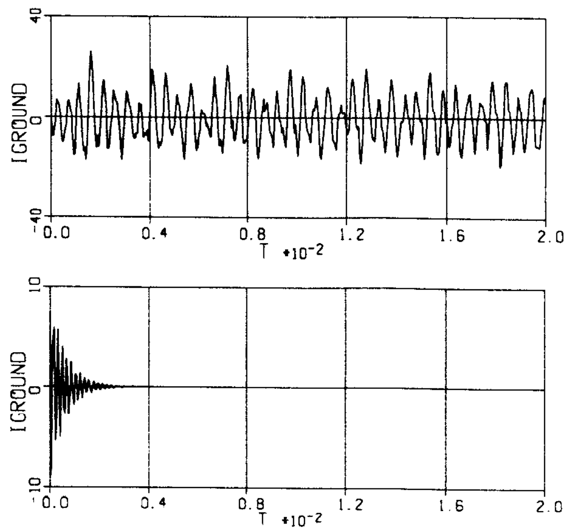

Figure 4: Simulated ground current for a 3 phase (upper) and for a 4 phase converter (lower)

Fig. 6 shows the measured filter neutral voltage with respect to earth ground for the topology shown in Fig. 5. One important parasitic effect introduced in the lab circuit is the common mode resonance introduced by the capacitor connected from the filter neutral to ground. However, in the four phase case, this resonance is not always present as shown in Fig. 6.

Fig. 7 shows the neutral voltage for a traditional three phase topology, using a traditional control strategy, sigma delta modulation. In the three phase case it is apparent that common mode voltage is always present to drive the resonance, thereby considerably increasing the neutral voltage excursions.

In practice realization of a nonzero neutral voltage is due to the fact that the filter components can never be perfectly balanced. Secondly, as shown in equation (14), the neutral voltage is not zero when the common mode impedance of the load is not infinite. Thirdly, the assumption of equation (1) is no longer valid; the pole voltages of the converter are controlled by the IGBT characteristics and this behavior is affected by the current level.

To address these and other deviations from the ideal system some additional filter components have been added and the control was modified somewhat. However, the additional components (capacitors) are very small (see Fig. 5).

In comparing Figs. 6 and 7 the most significant difference supports the simulation results. That is, the common mode voltage due to modulation energy is drastically reduced when the fourth phase is added to the filter (note the different scales in Figs. 6 and 7).

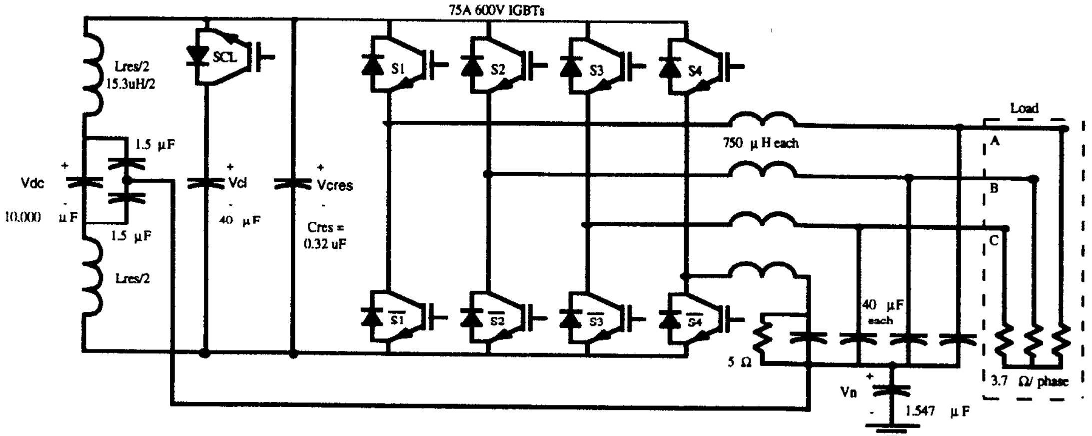

Figure 5: Schematic of the practical RDCL 4 phase converter

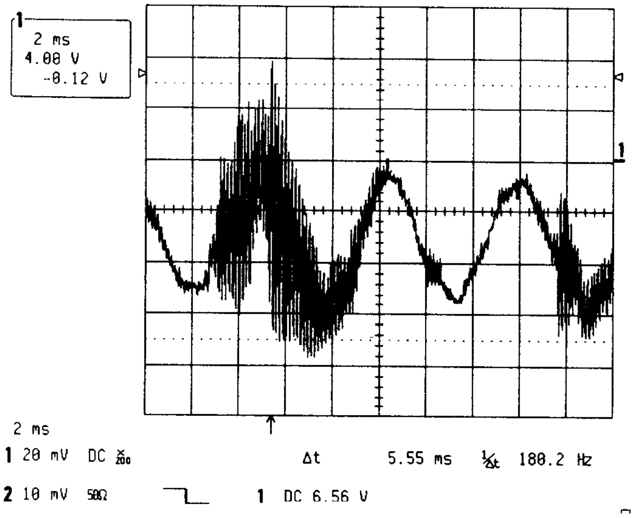

Figure 6: Measured V_n for 4 phase operation [4V/div]

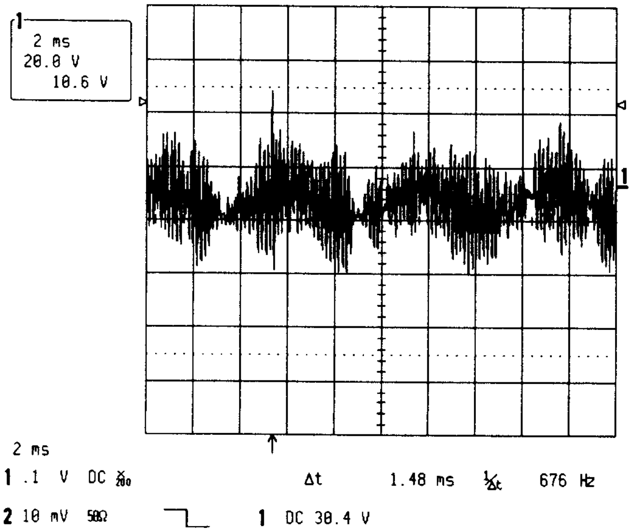

Figure 7: Measured V_n for 3 phase operation [20V/div]

Table 1: Amplitude of Significant Neutral to Earth Common Mode Voltage Components

Freq. (Hz)	4 Phase (dBV)	3 Phase (dBV)
87.5	-57.8	-59.7
180	-35.9	-35.8
265	-61.0	-64.8
540	-58.2	-54.4
900	-71.0	-63.9
5850	------	-33.6
6750	-47.4	------

The significant spectral components in the neutral voltage are shown in Table 1. Table 1 summarizes the significant peaks present in Fig. 8. For the four phase case, the modulation energy is centered at 6750 Hz and the amplitude is -47.4 dBV. For the three phase case the modulation energy is centered at 5850 Hz and the amplitude is -33.6 dBV. The peak of modulation energy is 5 times higher for the three phase case. If the transient resonances shown in Fig. 6 can be attenuated by means of feedback control of the inverter (active damping) then this modulation energy can be reduced even further. Examining Fig. 7 it should be noted that the oscillations are not transient phenomena but rather are persistent oscillations arising because the common mode voltage is always present in the three phase case. Fig. 8 shows the average spectra of the neutral voltage for the two converter topologies and provides an excellent contrast between 3 phase and 4 phase operation.

The neutral voltage component at 180 Hz is due to effects of the input diode rectifier. In Fig. 6 this component of common mode voltage is the dominant element because all of the other harmonics are reduced. The amplitude of this source harmonic does not change when the fourth leg of the inverter is added. This result is expected since the input common mode harmonics cannot be controlled by the inverter.

The fundamental output frequency is 87.5 Hz. A small third harmonic of the fundamental is present in the neutral voltage. Additonally, the third and fifth of 180 Hz due to the rectifier show up in the neutral voltage.

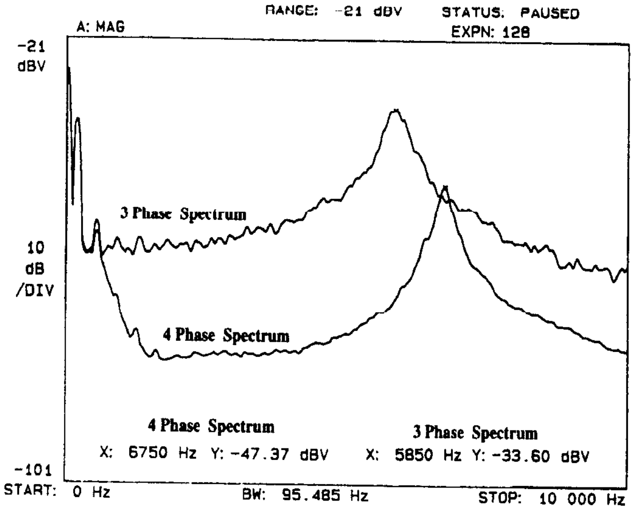

Figure 8: Measured frequency spectra of V_n for the three phase and four phase converters

Another aspect of interest is that the filter modification and modulation adaptation does not impact the line to line output voltage. Essentially no change in the output line to line voltage is measured. For the three phase case the THD in the first 20 harmonics is 1.3 % and for the four phase case the THD is 1.4 %.

VI. CONCLUSIONS

In this paper, a new strategy for minimizing the common mode voltage has been presented using the concept of a fourth "pseudo phase". Experimental measurements performed on a 4 phase resonant DC link (RDCL) show that the high frequency component of the common mode voltage is five times smaller than that measured in the three phase inverter, even though resonance problems arise in the experiment that were not included in the theoretical analysis. It should be mentioned that the work presented in this paper is only intended to validate the fact that the neutral voltage can be reduced in a four phase topology. With the numerous energy storage elements present in the filter much work remains to be done in identifying a more effective control strategy, including active damping to eliminate the passive damping elements in the present circuit. While the simulations predict a very small current in the fourth phase resonances were, however, observed in the lab hardware. The resolution of this problem is the next challenge in this effort.

APPENDIX

By writing the differential equations of the system shown in Fig. 1 with the constraint of equation (1) and the assumption that the filter and load are balanced, equation (14) can be computed where the coefficents are:

$$b_4 = 4L_F C_F L + 3C_F {L_F}^2 \tag{15}$$

$$b_3 = 4RL_F C_F + 4R_F C_F L + 6R_F C_F L_F \tag{16}$$

$$b_2 = 12L_F \frac{C_F}{C_g} + 4R_F C_F R + 4(L_F + L) + 3C_F {R_F}^2 \tag{17}$$

$$b_1 = 12R_F \frac{C_F}{C_g} + 4(R_F + R) \tag{18}$$

$$b_0 = \frac{12}{C_g} \tag{19}$$

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