A Five-Leg Inverter for Driving a Traction Motor and a Compressor Motor

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***Abstract*— This paper presents an integrated inverter for speed control of a traction motor and a compressor motor to reduce the compressor drive cost in EV/HEV applications. The inverter comprises five phase-legs; three of which are for control of a three-phase traction motor and the remaining two for a two-phase compressor motor with three terminals. The common terminal of the two-phase motor is tied to the neutral point of the three-phase traction motor to eliminate the requirement of a third phase leg. Further cost savings are made possible by sharing the switching devices, dc bus filter capacitors, gate drive power supplies, and control circuit. Simulation and experimental results are included to verify that speed control of the two motors is independent from each other.**

Keywords-EV/HEV traction drive; EV/HEV compressor drive; five-leg inverter; two-phase motor; zero-sequence current

I. Introduction

Because of their superior performance over the conventional engine belt-driven counterparts, electric motor driven compressors for heating, ventilating, and air-conditioning (HVAC) are being deployed in automobiles with a 42V power net and hybrid electric vehicles where a high voltage bus is readily available [1-4]. The advantages of electrically driven HVAC compressors include: (1) Highly efficient operation as the compressor speed can be adjusted independent of engine speed unlike the conventional belt driven unit, (2) Flexible packaging as the installation location is not restricted to the accessory drive side of the engine and, (3) Reduced leakage of the refrigerant into atmosphere because of the elimination of the rotating seals [4]. In addition, the electric compressor enables HEVs to shut-off the engine during vehicle stops or at low vehicle speeds when the engine power is not required. Moreover, fuel cell powered vehicles require an electrically driven HVAC compressor.

To reduce the cost of the automotive accessory drives, two-phase inverter-fed induction motor drives were used to replace wound-field or permanent magnet dc motors for heating, ventilating, demisting, engine-cooling, and water-pumping applications in the automotive industry [5–6]. Compared to a three-phase motor fed by a three-phase inverter, which typically requires six switches, a two-phase motor can be controlled by a lower cost two-leg inverter plus a split-capacitor leg as illustrated in Fig. 1. Unlike a semiconductor switch leg, the split-capacitor leg does not need additional gate drive or control circuits. Capacitors, however, have their own drawbacks such as lower reliability and a short service lifespan. These drawbacks become aggravated by the harsh environments expected in EV/HEV applications. It is therefore desirable to eliminate the split-capacitor leg.

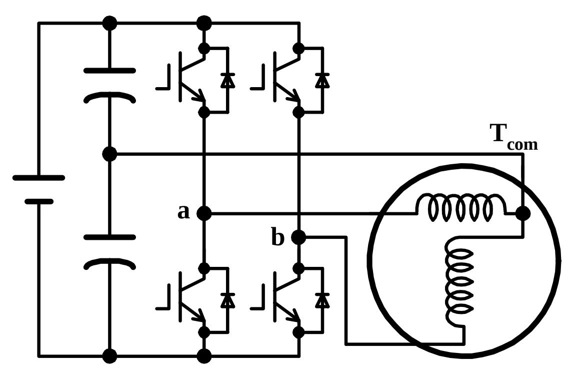

Figure 1. A low-cost two-phase motor drive using four switches and two capacitors.

This paper presents an integrated inverter of five legs for speed control of a three-phase traction motor and a two-phase compressor motor to further reduce the compressor drive cost. The two-phase inverter is first integrated into the three-phase inverter for the traction motor, so dc bus filter capacitors, gate drive power supplies and control circuit can be shared. Furthermore, the split-capacitor leg is eliminated by tying the common terminal of the two-phase motor to the neutral point of the three-phase traction motor. Therefore, integrating the compressor drive into the traction motor

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drive results in a lower cost, smaller volume drive system. Simulation and experimental results are included to verify that the speed of the two motors can be controlled independently from each other.

II. Proposed Integrated Inverter Topology

A. Description of the Proposed Inverter

Fig. 2 shows the proposed five-leg integrated inverter for driving a three-phase traction motor and a two-phase compressor motor. The inverter consists of a dc source, V_{dc}, a filter capacitor, C_1, and five phase legs, *U*, *V*, and *W* for feeding the traction motor, *a* and *b* for the compressor motor. The two-phase motor has two windings, phase-*a* and phase-*b*, and the two phase windings are connected at one end to form a common terminal, T_{com}, with the other ends remaining separated to form two independent phase terminals, T_a and T_b.

The first three legs of the inverter, *U*, *V* and *W* consisting of the switches S_1~S_6 form a three-phase main inverter, which through pulse width modulation provides three sinusoidal currents to the three-phase motor. The remaining two legs, *a* and *b*, are connected to the independent phase terminals of the two-phase motor, T_a and T_b, respectively, forming an auxiliary two-phase inverter. In addition, the common terminal, T_{com} is connected to the neutral point, *N* of the three-phase motor to eliminate the otherwise required split-capacitor phase leg. The two phase legs, *a* and *b*, by pulse width modulation, provide two sinusoidal currents with a phase shift of 90 electrical degrees to the two-phase motor. The sum of the two-phase currents, i_a and i_b, will split evenly into three parts and each part flows through one of the phase windings of the three-phase motor and the associated phase leg of the three-phase inverter as the return paths.

It is apparent that by integrating the two-phase auxiliary inverter into the main three-phase inverter, the dc bus filter capacitor and gate drive power supplies can be shared between the two inverters. In addition, a single control circuit typically based on a microprocessor or digital signal processor (DSP) with built-in motor control hardware such as A/D converters, PWM counters and encoder interface circuitry, can be used to execute control algorithms for the two motors. With a proper control algorithm, the motors can be run in either motoring mode. i.e., providing power to the motor shaft, or generating mode, in which power is transferred from the motor shaft to the inverter dc source.

B. Equivalent Circuits and PWM Considerations

Fig. 3(a) shows an equivalent circuit of the integrated drive system, in which the inverter is represented by five voltage sources, v_u, v_v, v_w, v_a and v_b, corresponding to the five phase legs, *U*, *V*, *W*, *a* and *b*, respectively. All the voltage sources are referred to the midpoint of the dc source, V_{dc}. By connecting the common terminal, T_{com} to the neutral point, *N* of the three-phase motor, the sum of the two-phase currents, i_N (= i_a + i_b), will split evenly into three parts and each part will flow through one of the phase windings of the three-phase motor and the associated phase leg of the three-phase inverter as the return paths, assuming a symmetrical three-phase motor and inverter. The two-phase motor currents are therefore zero-sequence components flowing in the three-phase stator and will have no effect on the operation of the three-phase motor because the zero-sequence currents will not produce torque, as shown in Fig. 3(b). In other words, the torque producing currents of the

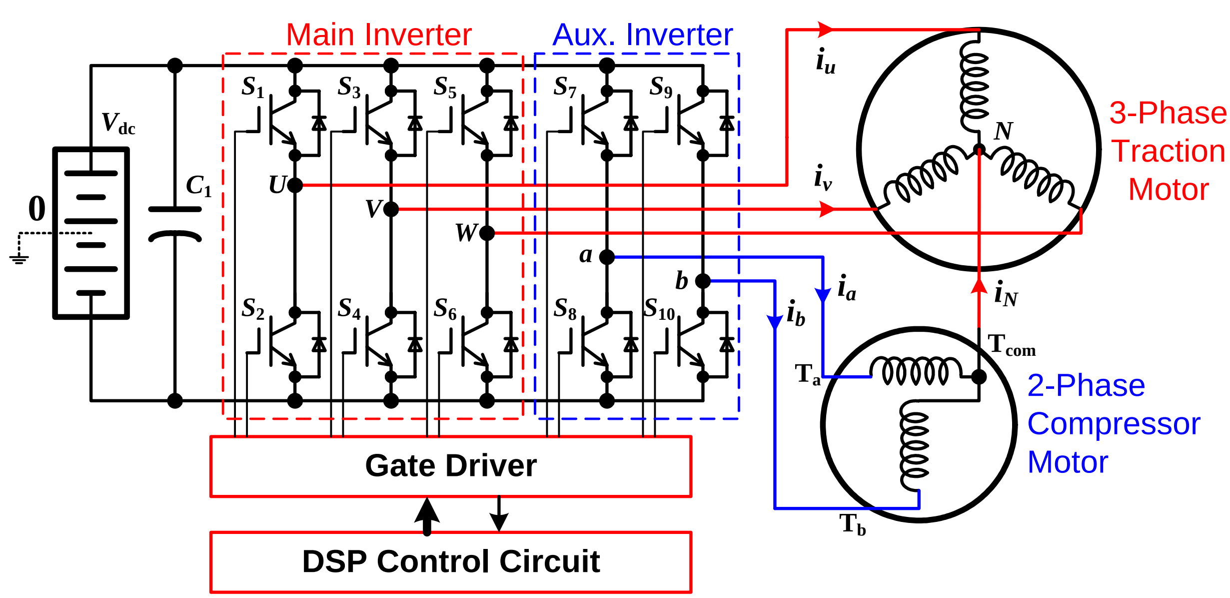


Figure 2. Proposed integrated inverter for driving a three-phase traction motor and a two-phase compressor motor.

two motors can be controlled independently.

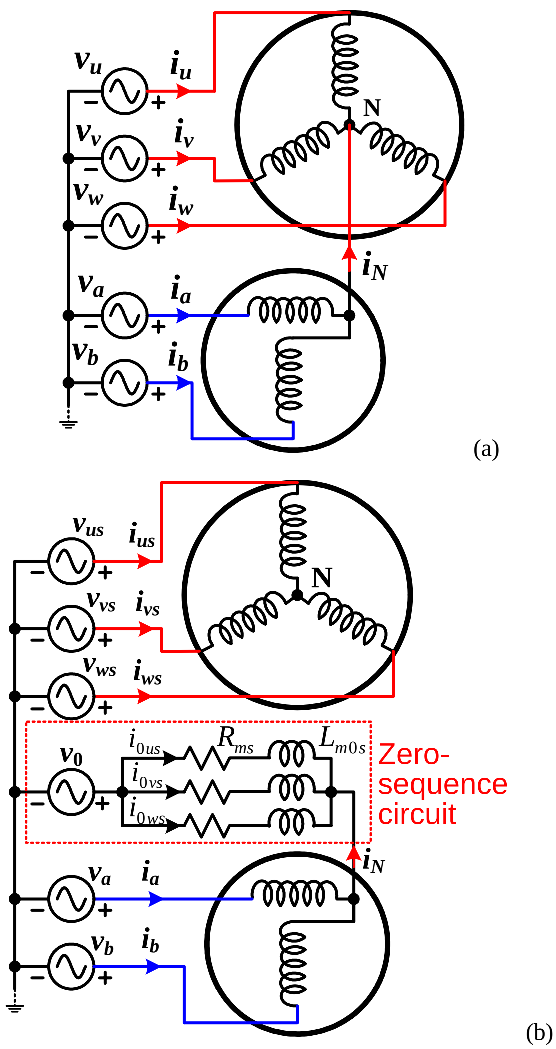


Figure 3. Equivalent circuits. (a) Showing inverter phase legs as voltage sources. (b) showing the zero-sequence circuit of the main motor as the current return path of the two-phase motor.

In Fig. 3(b), the zero-sequence circuit (ZSC) of the three-phase stator is separated from the positive and negative sequence circuits, where R_{ms} and L_{m0s} represent the resistance and inductance of the ZSC, and v_0 is the zero-sequence component of the three-phase voltage sources, v_u, v_v, and v_w, which may or may not exist depending on the PWM scheme. The zero-sequence voltage, v_0, can be calculated by:

$$v_0 = \frac{v_u + v_v + v_w}{3}. \tag{1}$$

v_{us}, v_{vs}, and v_{ws} are the phase voltages referenced to the zero-sequence voltage, of the three phases, *U*, *V*, and *W*, respectively, and are expressed by

$$\begin{cases} v_{us} = v_u - v_0 \\ v_{vs} = v_v - v_0 \\ v_{ws} = v_w - v_0 \end{cases}. \tag{2}$$

The zero-sequence voltage component, v_0, which could be generated by certain PWM strategies such as the space vector modulation schemes, can be cancelled by injecting the same component into the modulation signals for the two-phase inverter so that v_0 will not produce current in the circuit, as will be shown in the simulation and experimental results.

C. *Increase in the Current Rating of the Main Motor*

Because the stator windings of the three-phase motor are utilized as the current return paths of the two-phase motor, the stator current rating may need be increased to accommodate the two-phase motor currents. However, the increase of the main motor current is negligible if the two-phase motor current is sufficiently small compared to that of the main motor, which is typical in the intended automotive applications, as shown below.

The phase-*U* current of the main motor i_u can be expressed by

$$i_u = i_{us} - \frac{i_a + i_b}{3}, \tag{3}$$

where i_{us} is the required current if the three-phase motor is operated alone without connection to the two-phase motor. Because the two motor currents will usually have different frequencies, the rms value of the main motor phase current, i_u can therefore be calculated by

$$I_{u,rms} = \sqrt{I_{us,rms}^2 + \frac{2I_{a,rms}^2}{9}}, \tag{4}$$

where $I_{a,rms}$ is the required rms current of the two-phase motor. For instance, given a 350 Arms traction motor and a 25 Arms compressor motor, i.e. $I_{us,rms}$=350A and $I_{a,rms}$=25A, the resulting traction motor current is

$$\begin{aligned} I_{u,rms} &= \sqrt{I_{us,rms}^2 + \frac{2I_{a,rms}^2}{9}} \\ &= \sqrt{350^2 + \frac{2 \times 25^2}{9}}, \\ &= 350.2\text{Arms} \end{aligned} \tag{5}$$

giving a negligible increase of 0.2A, less than 0.06%.

III. Simulation and Experimental Results

Detailed circuit simulation and extensive testing were conducted to verify the proposed integated drive operations.

A. *Simulations*

Fig. 4 shows an equivalent circuit of the motors on the stator d-q frame for simulation, where the ZSC of the three-phase stator is separated from its positive/negative sequence counterparts and is inserted into the current path of the two-phase motor. A detailed derivation of the equivalent circuit and the simulation work will be described in a future publication.

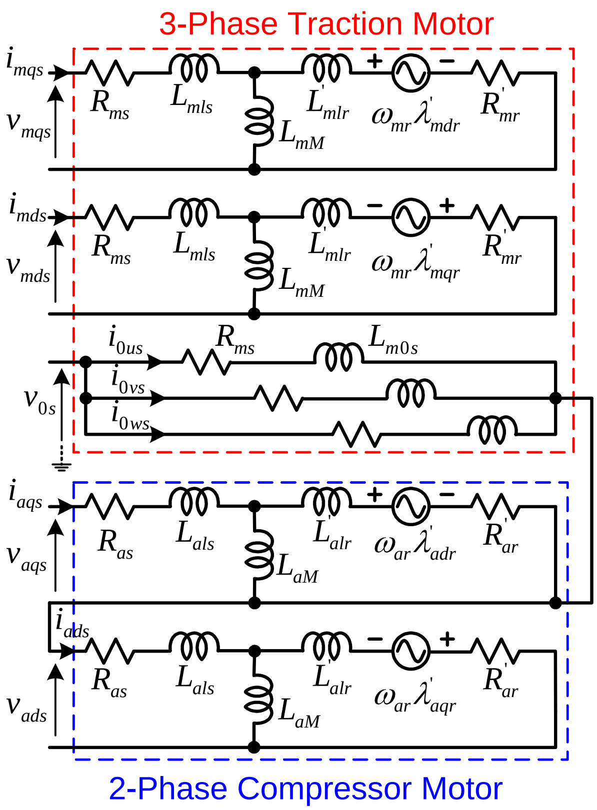
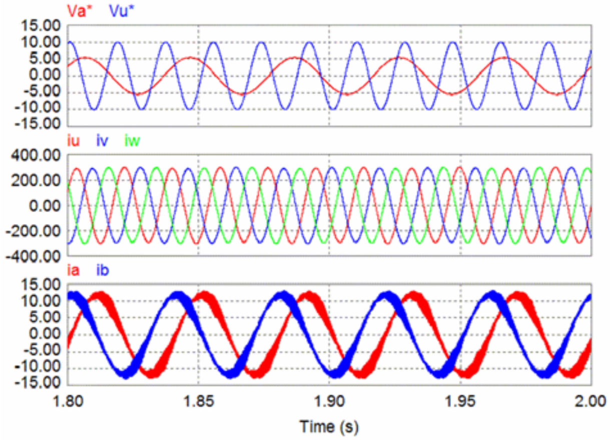
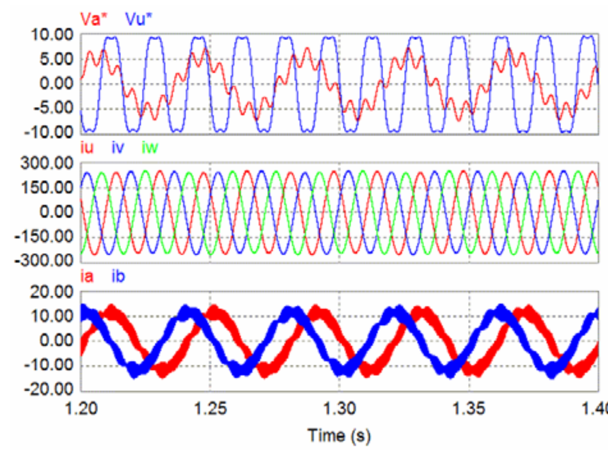


Figure 4. An equivalent circuit on stator d-q frame for simulation.

Fig. 5 shows simulated motor current waveforms when the two motors operate at different speeds, where *Vu** and *Va** are modulation signals for the three-phase motor phase-*U* and the two-phase motor phase-*a*, respectively. In Fig. 5 (a), a sine-triangle comparison PWM scheme is used without third-harmonic injection and thus there are no zero-sequence components in the three-phase voltages, i.e. v_0=0. In contrast, a third harmonic is added to the modulation signals for the three-phase inverter in (b), resulting in a zero-sequence voltage component, i.e. $v_0 \neq 0$. By injecting the same third harmonic component into the two-phase modulation signals, v_0 can be cancelled and no third harmonic current is produced.



(a) v_0=0.

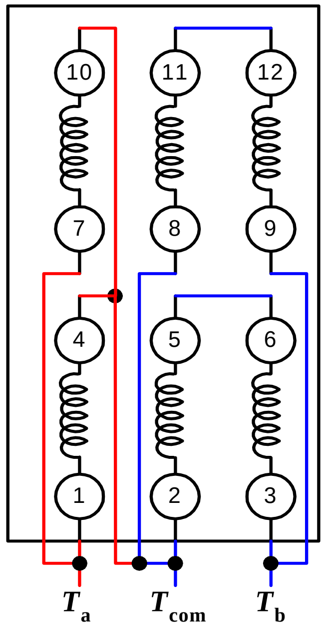


(b) $v_0 \neq 0$.

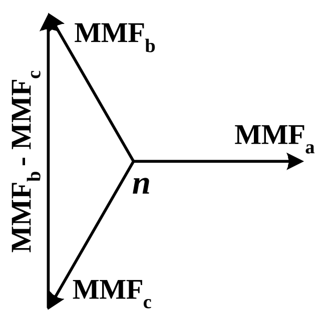
Figure 5. Simulation results.

B. *Experimental Setup*

For testing, a 15 HP, 230/460V, six-pole, three-phase induction motor was used as the traction motor. The motor has two sets of stator windings that can be connected in series for 460V or in parallel for 230V operations. All winding terminals are accessible because it is intended to use a Y connection for starting and then a Δ connection for normal run. In our testing, each winding set is wired as a Y connection and then the two sets are connected in parallel. For the compressor motor, a 2 HP, 230/460V, three-phase, two-pole motor, which also has two sets of stator windings, was modified to form a two-phase motor as shown in Fig. 6 (a). To reduce the dc bus voltage requirement, the two phase-*a* windings are connected in parallel, and each of the phase-b and phase-c windings are connected in series and then in parallel. This connection results in equivalently an asymmetrical two-phase motor of two orthogonal windings with a turns ratio of $\sqrt{3}:1$, as can be seen from the magnetomotive force vectors shown in Fig. 6 (b).



(a) Stator winding connection

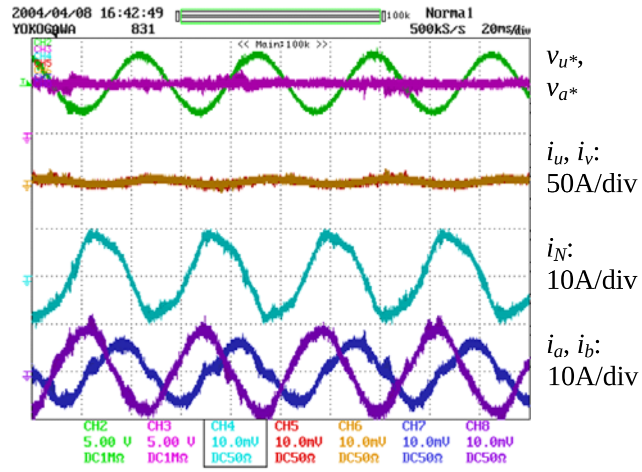


(b) Magnetomotive force vectors

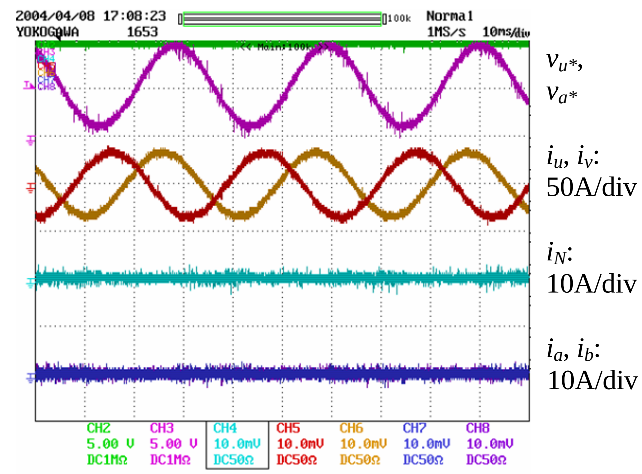
Figure 6. Wiring connection of a 3-phase motor for producing a 2-phase motor.

C. *Experimental Results*

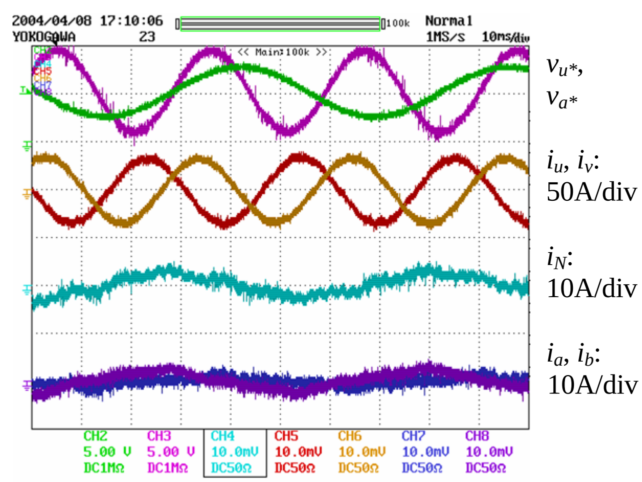
Fig. 7(a) ~ (f) give testing waveforms at various load conditions and without the zero-sequence components in the three-phase voltages, i.e. v_0=0, which clearly shows that speed of the two motors can be controlled independently. In (a), the main motor was not running while the two-phase motor was loaded with 220 oz·in (1.55 N·m) at 1000 rpm. In (b), the main motor was loaded with 65N·m at 610 rpm and the two-phase motor was not running. In (c), the main motor was loaded with 65 N·m at 610 rpm while the two-phase motor ran at 1100 rpm with no load. In (d), the main motor ran at 1000 rpm with no load, while the two-phase motor was loaded with 220 oz·in (1.55 N·m) at 992 rpm. In (e), the main motor was loaded with 65.1 N·m at 610 rpm, while the two-phase motor was loaded with 221 oz·in (1.56 N·m) at 898 rpm. In (f) the main motor was loaded with 91 N·m at 541 rpm, while the two-phase motor was loaded with 325 oz·in (2.30 N·m) at 963 rpm. It should be noted that because of their asymmetrical windings, the two-phase motor currents, i_a and i_b, are not equal.



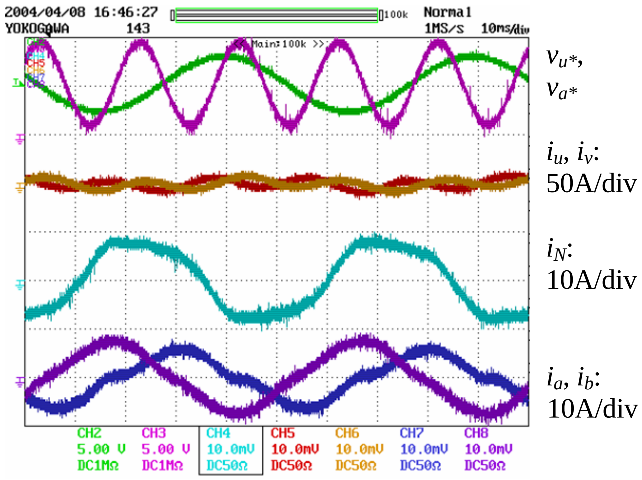
(a) Main motor is not running while 2-phase motor loaded with 220 oz·in (1.55 N·m) at 1000 rpm. 20ms/div



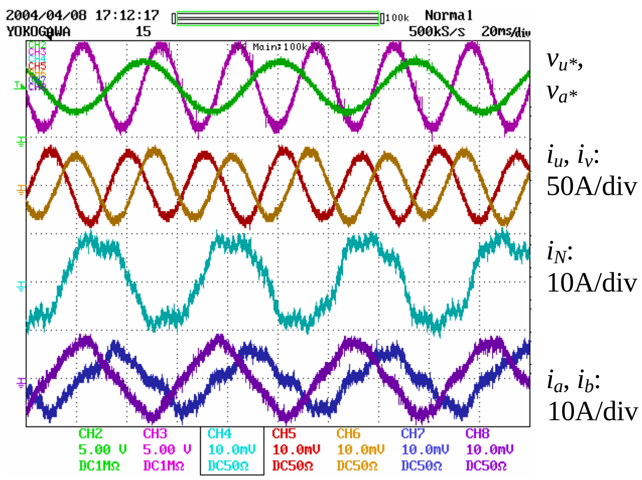
(b) Main motor is loaded with 65 N·m at 610 rpm, while 2-phase motor is not running. 10ms/div



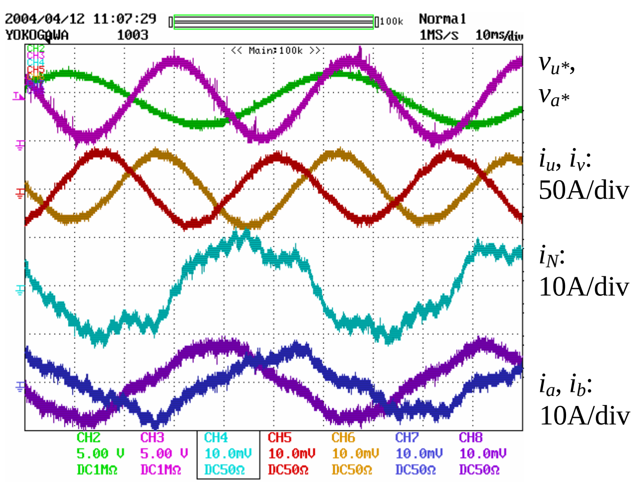
(c) Main motor is loaded with 65 N·m at 610 rpm, 2-phase motor at 1100 rpm, no load. 10ms/div



(d) Main motor at 1000 rpm, no load, 2-phase motor loaded with 220 oz·in (1.55 N·m) at 992 rpm. 10ms/div



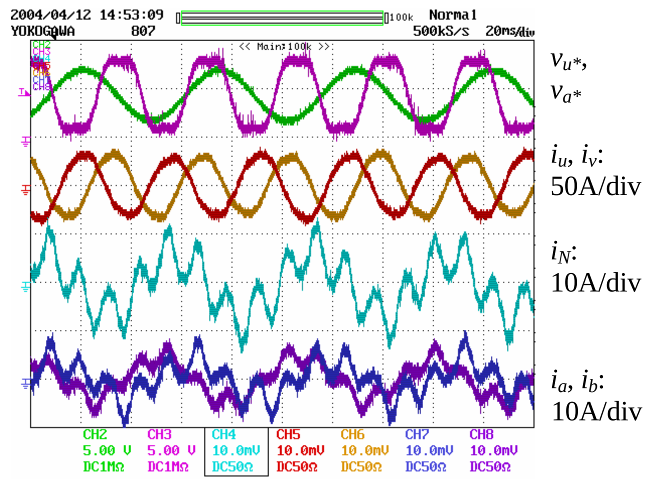
(e) Main motor loaded with 65.1N·m at 610 rpm, 2-phase motor loaded with 221 oz·in (1.56 N·m) at 898 rpm. 20ms/div



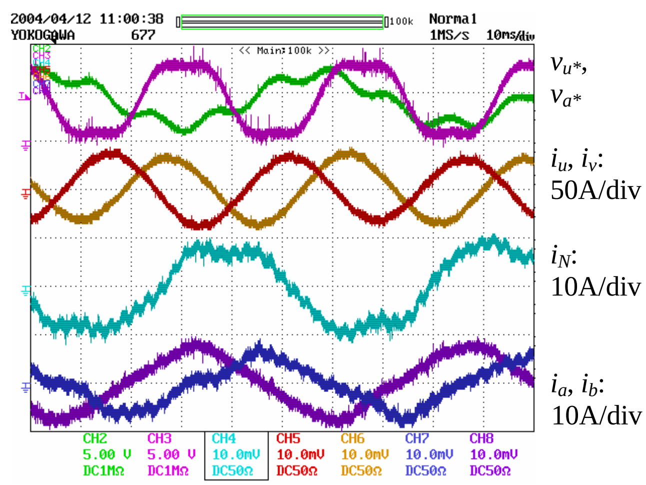
(f) Main motor loaded with 91 N·m at 541 rpm, 2-phase motor loaded with 325 oz·in (2.30 N·m) at 963 rpm. 10ms/div

Figure 7. Testing waveforms at various load conditions showing that the speed of the two motors can be controlled independently.

A third harmonic current was generated when the three-phase modulation signals contain a third harmonic, which is a zero sequence component, i.e. $v_0 \neq 0$, as shown in Fig. 8 (a), where the main motor was loaded with 85 N·m at 544 rpm and the two-phase motor was loaded with 221 oz·in (1.56 N·m) at 1040 rpm. By adding the same third harmonic to the two-phase modulation signals, no third harmonic current was produced, as illustrated in (b), where the main motor was loaded with 91 N·m at 542 rpm and the two-phase motor was loaded with 325 oz·in (2.30 N·m) at 966 rpm.



(a) Main motor loaded with 85 N·m at 544 rpm, 2-phase motor loaded with 221 oz·in (1.56 N·m) at 1040 rpm. 20ms/div



(b) Main motor loaded with 91 N·m at 542 rpm, 2-phase motor loaded with 325 oz·in (2.30 N·m) at 966 rpm. 10ms/div

Figure 8. Testing waveforms showing that third harmonic components in the three-phase voltages can be prevented from producing current.

IV. CONCLUSIONS

The proposed integrated traction and compressor motor drive using a five-leg inverter can significantly reduce the cost of the compressor motor drive in EV/HEV applications. The simulation and testing results show that:

- The split-dc bus capacitors for a two-phase compressor motor drive can be eliminated by using the traction motor stator windings as the current return paths.
- Increase in the current rating of the main inverter switches and the traction motor due to the two-phase motor current is negligible.
- Speed of the traction and compressor motors can be controlled independently from each other. The test results on the independent control characteristics of the two motors and on the voltage waveforms agree fully with the analytical predictions.
- The fundamental components of the two motors have no influence on each other.

While induction motors are discussed in this paper, the proposed inverter is applicable to ac synchronous permanent magnet machines and brushless dc motors.

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