Pulse-Width-Modulation Schemes for an Integrated Traction and Compressor Drive System

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***Abstract*— This paper presents pulse-width-modulation schemes for an integrated traction and compressor drive system for automotive applications. The integrated drive system employs a five-leg inverter to control a three-phase traction motor and a two-phase compressor motor and can significantly reduce the component count of the compressor drive for heating, ventilating and air-conditioning in fuel cell and hybrid electric vehicles. Because the common terminal of the two-phase motor is tied to the neutral point of the three-phase traction motor, PWM schemes that generate a zero-sequence voltage to the three-phase motor may produce an unwanted zero-sequence current. This paper presents PWM strategies for the two-phase motor to avoid this zero-sequence current and discusses in detail three commonly used three-phase PWM schemes. Experimental results are included to verify the effectiveness of the proposed methods.**

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 (HEVs) where a high voltage bus is readily available [1-4]. The advantages of electrically driven HVAC compressors include: (1) More efficient operation as the compressor speed can be adjusted independently of engine speed unlike the conventional belt driven unit; (2) Flexible packaging as the 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. In addition, the electric compressor enables HEVs to shut off the engine during vehicle stops or at low vehicle speed when the engine power is not required. Moreover, fuel cell powered vehicles require an electrically driven HVAC compressor.

An integrated drive system that employs a five-leg inverter for control of a three-phase traction motor and a two-phase compressor motor was proposed in [7] to reduce the compressor drive cost. Compared to the commonly used three-phase motor drive or a standalone two-phase motor drive [5–6], the integrated drive eliminates one switch-leg or capacitor-leg in the compressor drive. In addition, dc bus filter capacitors, gate drive power supplies and control circuit can be shared between the traction and compressor drive inverters. Furthermore, the increase in the current ratings of the traction motor and inverter is negligible because the rated current of the compressor motor is much smaller than that of the traction motor. Therefore, the use of a two-phase motor and the integration of the compressor drive into the traction motor drive can significantly reduce the component count and thus the cost and volume of the compressor drive.

In the integrated drive, because the common terminal of the two-phase motor is tied to the neutral point of the three-phase traction motor to provide current return paths for the two-phase motor via the stator windings of the three-phase motor and the three-phase inverter, pulse width modulation (PWM) schemes that generate a zero-sequences voltage to the three-phase motor may produce an unwanted zero-sequence current. This paper presents PWM strategies for the two-phase motor to avoid this zero-sequence current and discusses in detail three commonly used three-phase PWM schemes including the 3rd harmonic injected sine comparison PWMs, space vector PWMs and bus clamped PWMs [9]. Experimental results are included to verify the effectiveness of the proposed methods.

II. INTEGRATED TRACTION AND COMPRESSOR DRIVE TOPOLOGY

A. *Description of the Integrated Drive*

Fig. 1 shows the proposed integrated drive system employing a five-leg inverter for controlling a three-phase traction motor and a two-phase compressor motor. The

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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, and *a* and *b* for the compressor motor. The two windings, phase-*a* and phase-*b*, of the two-phase motor 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 motoring mode to provide power to the motor shaft, or generating mode to transfer motor shaft power to the inverter dc source.

B. Equivalent Circuits

Fig. 2(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 as shown in Fig. 2(b) and as such will have no effect on the operation of the three-phase motor because the zero-sequence currents will not produce air-gap flux or torque. In other words, the torque producing currents of the two motors can be controlled independently from each other; this independent speed and torque control of the two motors was verified by simulation and experimental results in [7-8]. Moreover, with the integrated system, a single control circuit, typically based on a microprocessor or digital signal processor (DSP), may be used to execute control algorithms for the two motors.

Fig. 2(b) also illustrates that it is the zero-sequence circuit of the three-phase motor that provides the return paths for the two-phase motor currents.

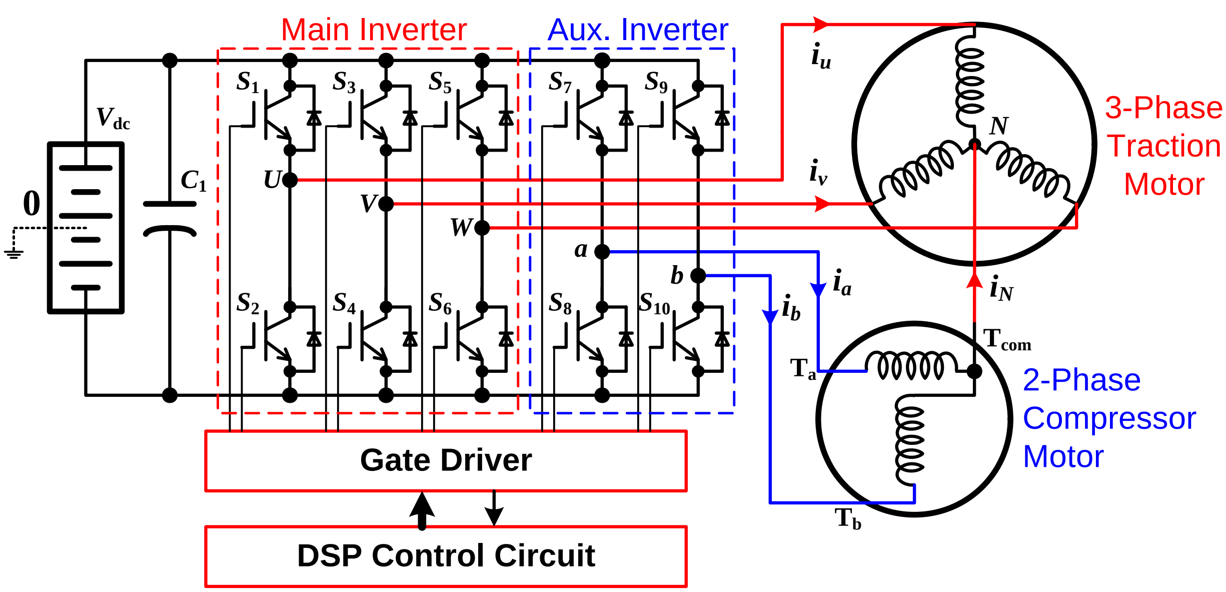
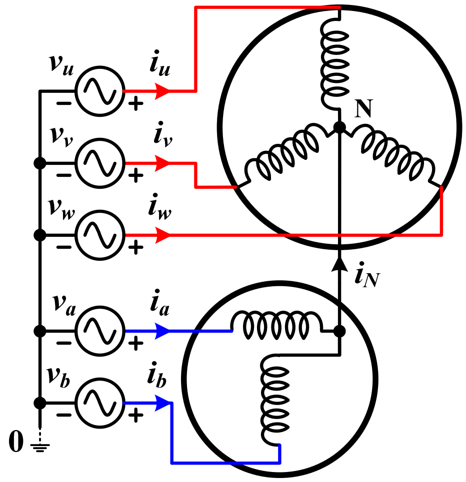
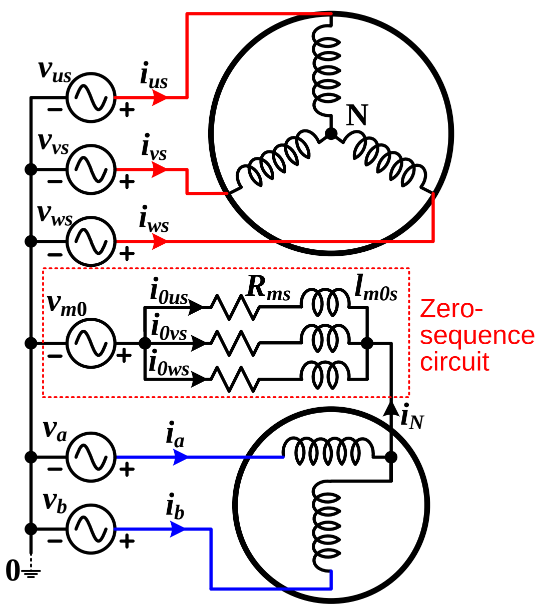


Figure 1. Proposed integrated drive of a three-phase traction motor and a two-phase compressor motor.



(a) An equivalent circuit showing the stator windings of the main motor as the current return path of the two-phase motor



(b) An equivalent circuit showing the zero-sequence circuit of the main motor as the current return path of the two-phase motor

Figure 2. Equivalent circuits of the integrated three-phase and two-phase motor drive system.

In Fig. 2(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_{m0} 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_{m0}, can be calculated by:

$$v_{m0} = \frac{v_u + v_v + v_w}{3}, \quad (1)$$

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

$$\begin{cases} v_{us} = v_u - v_{m0} \\ v_{vs} = v_v - v_{m0} \\ v_{ws} = v_w - v_{m0} \end{cases}. \quad (2)$$

The zero-sequence voltage component, v_{m0}, 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_{m0} will not produce current in the circuit, details of which will be discussed in the following sections.

III. PWM Schemes for the Integrated Traction and Compressor Drive System

A. *Cancellation of Zero-Sequence Voltage*

To prevent the unwanted zero-sequence current, the same zero-sequence voltage can be added to the two-phase inverter as shown in Fig. 3, in which v_{m0} represents the zero-sequence component of the three-phase voltage sources, v_u, v_v, and v_w, generated by certain PWM schemes and can be calculated by (1).

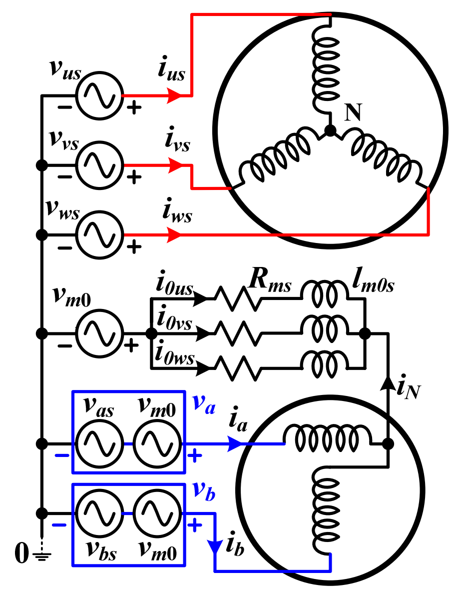


Figure 3. An equivalent circuit showing the cancellation of the zero-sequence voltage, v_{m0}.

To cancel the zero-sequence voltage component, v_{m0}, the same component is injected into the modulation signals for the two-phase inverter so that v_{m0} will not produce current in the circuit, as will be shown in the experimental results. Fig. 4 shows a conceptual block diagram to implement the cancellation method. The zero-sequence component, v_{m0}, can be extracted from the three-phase modulation signals, v_{um}, v_{vm} and v_{wm}, which are produced by the pulse width modulator based on the three phase voltage references, v_{usref}, v_{vsref} and v_{wsref}, and are added to the two-phase reference voltages, v_{asref} and v_{bsref}. Therefore, the same zero-sequence voltage appears on all five phase voltages, canceling each other.

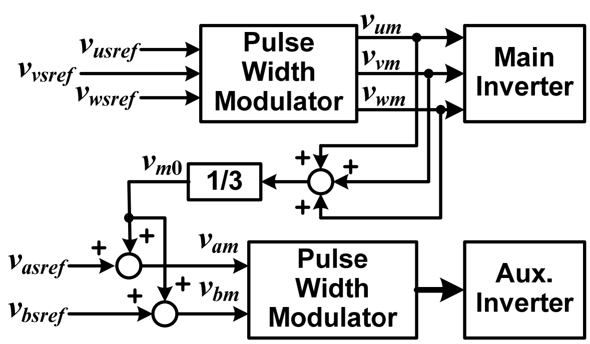


Figure 4. A pulse width modulation scheme for cancellation of the zero-sequence voltage.

B. *Implementation for Common PWM Schemes*

Implementations, with a digital signal processor, for three commonly used PWM methods, i.e. the 3rd harmonic injected sine comparison, space vector modulation and bus clamped two-phase modulation, are discussed in detail for the three phase sinusoidal reference voltages,

$$\begin{cases} v_{uref} = V_m \cos\omega t \\ v_{vref} = V_m \cos(\omega t - \frac{2\pi}{3}) \\ v_{wref} = V_m \cos(\omega t + \frac{2\pi}{3}) \end{cases} . \quad (3)$$

The three phase modulation voltages, v_{um}, v_{vm} and v_{wm}, are then synthesized by adding an offset voltage, which is the zero-sequence voltage, v_{m0}, to each of the three reference voltages. v_{um}, v_{vm} and v_{wm} can be expressed by

$$\begin{cases} v_{um} = v_{uref} + v_{offset} \\ v_{vm} = v_{vref} + v_{offset} \\ v_{wm} = v_{wref} + v_{offset} \end{cases} . \quad (4)$$

Computation of the offset voltages for the three PWM schemes are discussed below.

1) 3rd Harmonic Injected Sine Comparison PWM: In this scheme, a harmonic component with a frequency three times and amplitude one-sixth the fundamental component is added to the three phase reference voltages and the zero-sequence voltage, v_{m0}, can be calculated by:

$$v_{m0} = \frac{V_m}{6}\cos 3\omega t . \quad (5)$$

2) Space Vector Modulation: For the center symmetrical space vector modulation, the offset voltage can be computed over six segments of 60 electrical degrees in a fundamental cycle as

$$v_{offset} = \begin{cases} \frac{V_m}{2}\sin(\omega t - \frac{\pi}{6}) & \omega t \in [0, \frac{\pi}{3}], [\pi, \frac{4\pi}{3}] \\ \frac{V_m}{2}\cos\omega t & \omega t \in [\frac{\pi}{3}, \frac{2\pi}{3}], [\frac{4\pi}{3}, \frac{5\pi}{3}] \\ -\frac{V_m}{2}\sin(\omega t + \frac{\pi}{6}), & \omega t \in [\frac{2\pi}{3}, \pi], [\frac{5\pi}{3}, 2\pi] \end{cases} . \quad (6)$$

3) Bus Clamped Two-Phase Modulation: An offset voltage is added to the three phase reference voltages so that only two phase legs perform pulse width modulation over a period of 60 electrical degrees with the remaining phase leg clamped to the positive or negative dc bus rail. The offset voltage, i.e. the zero-sequence voltage, is determined by

$$\begin{aligned} v_{offset} &= V_{m\_max} - \max(v_{usref}, v_{vsref}, v_{wsref}) \quad \textit{if} \\ &\max(v_{usref}, v_{vsref}, v_{wsref}) > |\min(v_{usref}, v_{vsref}, v_{wsref})|, \quad (7) \\ v_{offset} &= |\min(v_{usref}, v_{vsref}, v_{wsref})| - V_{m\_max} \quad \textit{else} \end{aligned}$$

where V_{m_max} represents the maximum amplitude of the phase voltages that the inverter can produce.

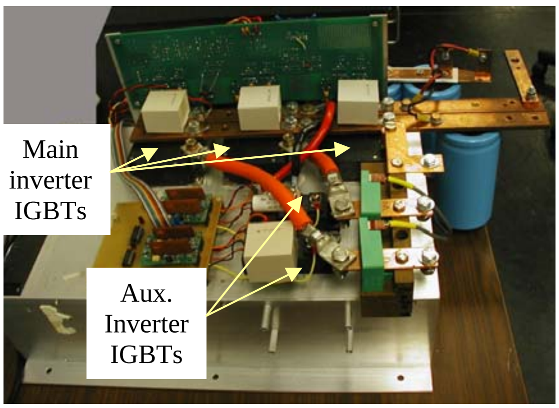
It is clear now that the offset voltages are essentially triple harmonics and thus will produce triple harmonic zero-sequence currents if the offset voltages are not cancelled.

IV. EXPERIMENTAL RESULTS

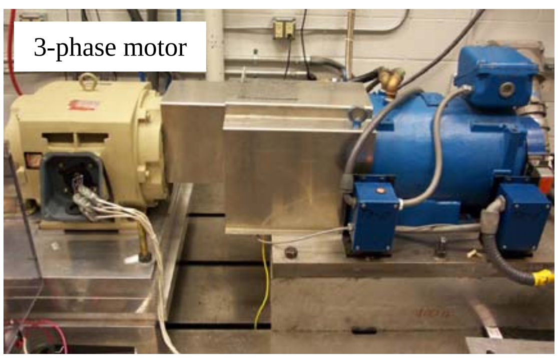
Extensive testing was conducted to verify the effectiveness of the proposed PWM methods.

A. *Experimental Setup*

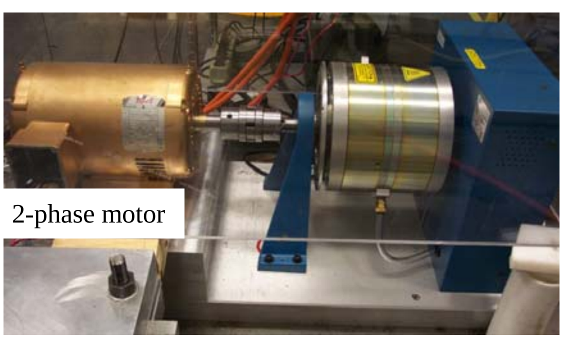
In the testing, a 15 HP, 230/460V, six-pole, three-phase induction motor was used as the traction motor. The motor has two sets of stator windings that can be connected in series for 460V or in parallel for 230V operation in Δ connection. All winding terminals are accessible because it is intended to 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 to reduce the dc bus voltage requirement. For the compressor motor, a 3 HP, 230/460V, three-phase, four-pole motor, which also has two sets of stator windings, was rewound into a two-phase motor. To reduce the dc bus voltage requirement, the two sets of windings are also connected in parallel. The rated current and torque are 22 A and 90 N·m for the three-phase motor, and 13 A and 12.5 N·m for the two-phase motor, respectively. An inverter was fabricated with three 600V/400A dual-pack IGBT modules for the main inverter and two 600V/75A dual-pack IGBT modules for the auxiliary inverter. The three PWM schemes were implemented with a TI TMS320F240 DSP. Fig. 5 shows photos of the inverter, main motor mounted on a 100 HP dynamometer test bed and the two-phase motor connected to a hysteresis dynamometer.



(a) Inverter



(b) Main motor mounted on a 100 HP dynamometer test bed

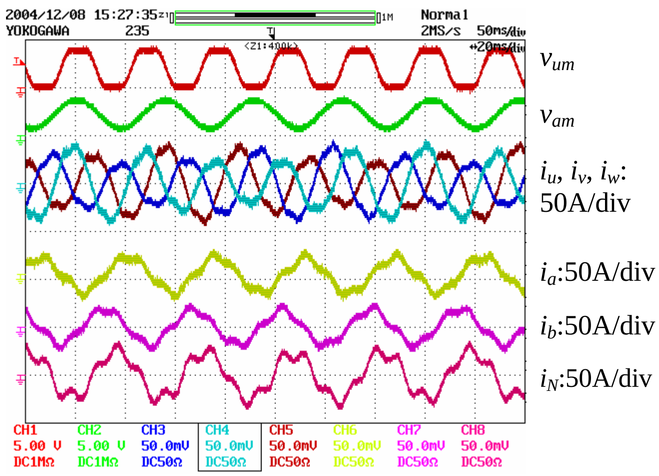


(c) Two-phase motor connected to a hysteresis dynamometer

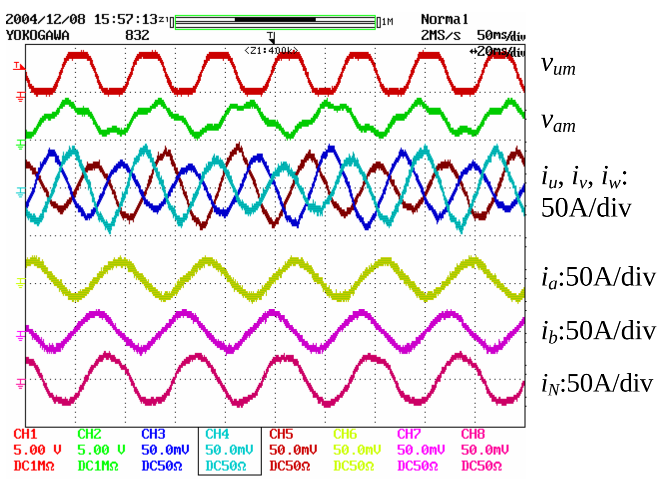
Figure 5. Photos of the inverter and motors testing setup.

B. *Experimental Results*

Figs. 6 ~ 8 show a comparison of motor currents waveforms before in (a) and after in (b) the cancellation of the zero-sequence voltage for the 3rd harmonic injected PWM, space vector PWM and bus clamped two-phase modulation, respectively. As predicted, triple harmonic currents were generated as zero sequence current when the offset voltage was not cancelled. After turning on the proposed zero-sequence voltage cancellation scheme the zero-sequence current due to the PWM methods were prevented.



(a) Before the zero-sequence cancellation. 20ms/div

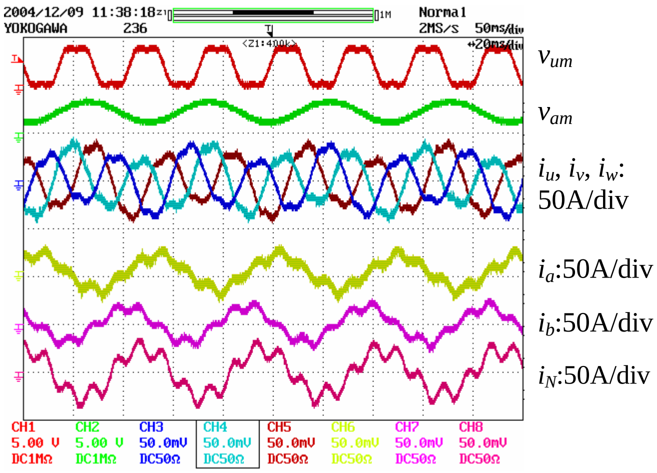


(b) After the zero-sequence cancellation. 20ms/div

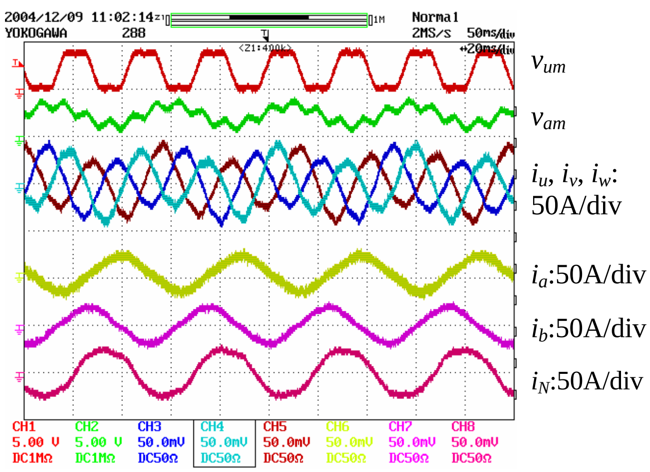
Figure 6. Comparison of motor currents waveforms for the 3rd harmonic injected PWM. Main motor loaded with 90 N·m at 690rpm, while 2-phase motor loaded with 14.7 N·m at 750rpm.

V. CONCLUSIONS

This paper presents pulse-width-modulation schemes for an integrated traction and compressor drive system for automotive applications. The proposed PWM strategies for the two-phase motor can avoid the unwanted triple harmonic zero-sequence currents. Three commonly used three-phase PWM schemes are discussed in detail, implemented in a DSP and tested. Experimental results verified the effectiveness of the proposed zero-sequence cancellation method.



(a) Before the zero-sequence cancellation. 20ms/div



(b) After the zero-sequence cancellation. 20ms/div

Figure 7. Comparison of motor currents waveforms for the space vector PWM. Main motor loaded with 90 N·m at 690rpm, while 2-phase motor loaded with 12.7 N·m at 500rpm.

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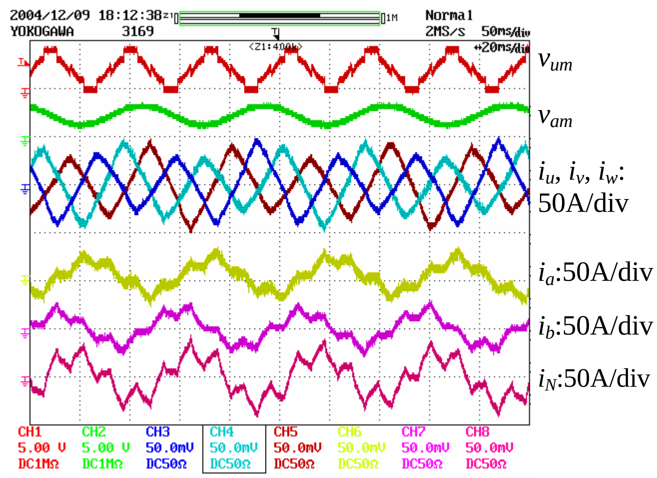
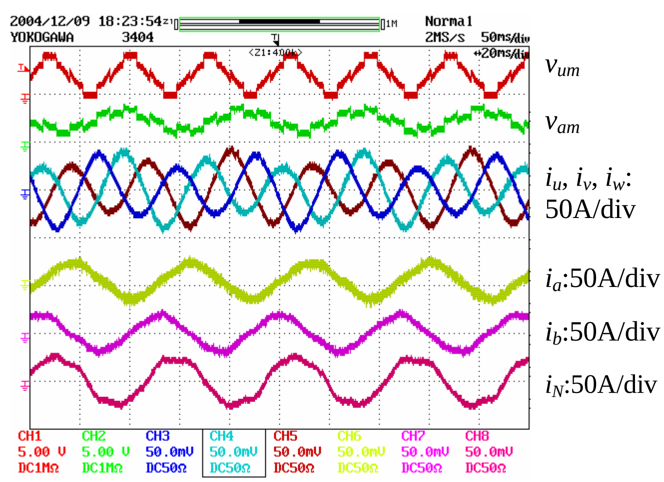


(a) Before the zero-sequence cancellation. 20ms/div



(b) After the zero-sequence cancellation. 20ms/div

Figure 8. Comparison of motor currents waveforms for the bus clamped PWM. Main motor loaded with 90 N·m at 600rpm, while 2-phase motor loaded with 12.2 N·m at 500rpm.