AN INTEGRATED TRACTION AND COMPRESSOR DRIVE SYSTEM FOR EV/HEV APPLICATIONS

Electric and hybrid electric vehicles (EVs/HEVs) require an electric motor driven compressor for heating, ventilating, and air-conditioning (HVAC). While current HEVs employ a standalone inverter controlled compressor motor drive, integrating the traction and compressor drive presents a new approach to reduce the component count, size, weight and cost of the HVAC compressor drive by eliminating two power semiconductor switches and by sharing the other switches, dc bus filter capacitors, gate drive power supplies, and a single digital signal processor (DSP) or microprocessor control circuit.

Because of their superior performance over their conventional engine belt-driven counterparts, HVAC electric motor driven compressors are being deployed in automobiles with a 42V power net and HEVs where a high-voltage bus is readily available. The advantages of electrically driven HVAC compressors include: (1) highly efficient operation, as the compressor speed can be adjusted according to cooling/heating requirements, independent of engine speed; (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 the atmosphere, because of the elimination of rotating seals. 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, future automotive applications may require an electrically driven HVAC compressor if the potential transition is made to fuel cell powered vehicles.

Figure 1 shows a conventional drive configuration using two separate inverters, one for the traction drive and the other for the compressor motor. While most compressor drives employ a three-phase inverter and a three-phase motor as shown in the figure, to reduce the cost, two-phase inverter-fed induction motor drives were proposed to replace wound-field or permanent magnet dc motors for heating, ventilating, demisting, engine-cooling, and water-pumping applications in the automotive industry. Compared to a three-phase motor fed by a three-phase inverter, a two-phase motor can be controlled by a lower cost two-leg inverter plus a split-capacitor leg as illustrated in Figure 2. Unlike a semiconductor switch leg, the split-capacitor leg does not need additional gate drives or control circuits, thus making it cheaper than a semiconductor switch leg. In addition, manufacturing cost is lower for a two-phase motor than for its three-phase counterpart due to the elimination of the assembly cost of one phase winding.

It is apparent that the number of components can be reduced by simply integrating the two-phase inverter with the three-phase traction inverter, as the control circuit, dc bus filter capacitor, and possibly some of the gate drive power supplies can be shared. Electrolytic capacitors, while frequently used in industrial and commercial applications due to their volumetric efficiency and lower cost,

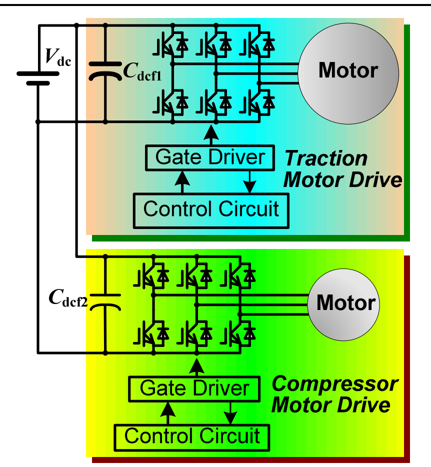

Figure 1. A conventional traction and compressor motor drive configuration using two separate inverters.

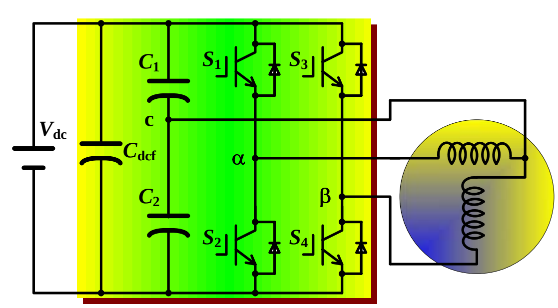

Figure 2. A low-cost two-phase motor drive using four switches and two capacitors for automotive HVAC compressor drive applications.

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have a low reliability and a short service lifespan. They are being replaced by film or ceramic capacitors in EV/HEV applications because of the harsh environments expected in those applications. Film and ceramic capacitors, however, are costly and have a large volume for the same amount of capacitance. It is therefore desirable to eliminate the split-capacitor leg. This is accomplished in an integrated traction and compressor drive developed at the Oak Ridge National Laboratory.

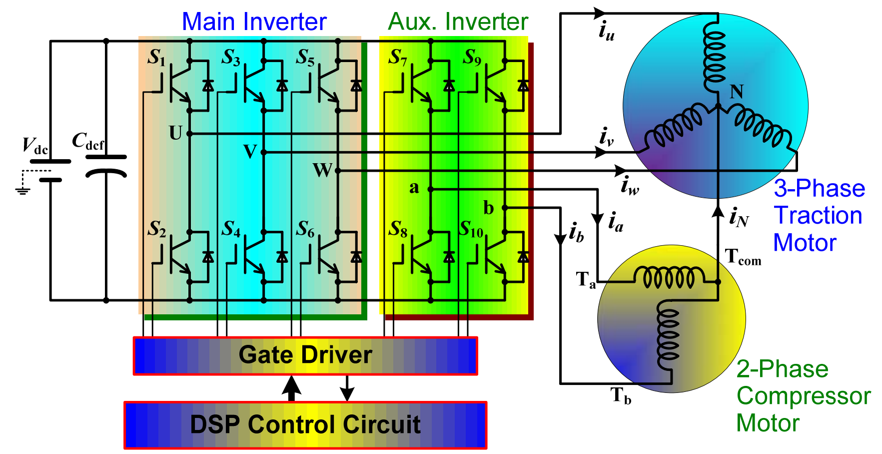


Figure 3. The integrated system for driving a three-phase traction motor and a two-phase compressor motor.

DESCRIPTION OF THE INTEGRATED TRACTION AND COMPRESSOR DRIVE SYSTEM

Figure 3 shows the integrated drive system that employs a five-switch-leg 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_{dcf}, and five phase-legs, U, V, and W for feeding the traction motor, and a and b for the compressor motor. The two-phase motor has two orthogonal windings, phase-a and phase-b, and they 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* consist of the switches S_1-S_6 which forms a three-phase main traction inverter, which through pulse width modulation (PWM) provides three sinusoidal currents to the three-phase traction motor. The remaining two legs, a and b, are connected to the independent phase terminals of the two-phase compressor 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 need for a split-capacitor phase leg. The two phase-legs, a and b, provide two sinusoidal currents, through PWM, 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 return through the stator windings of the three-phase motor and the associated phase legs of the three-phase inverter. With a proper control algorithm, the traction motor 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.

The integrated drive reduces the components count of the compressor drive by more than one-third through the elimination of one phase leg and the sharing of the dc bus filter capacitor and gate drive power supplies for the bottom switches. In addition, a single control circuit typically based on a microprocessor or 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. The integration of the two drives in this way, thus, results in a lower cost and smaller volume compressor drive.

EQUIVALENT CIRCUITS AND CONSIDERATIONS OF PWM SCHEMES

Figure 4(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, and 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 can be seen from Figure 4(b). In other words, the torque

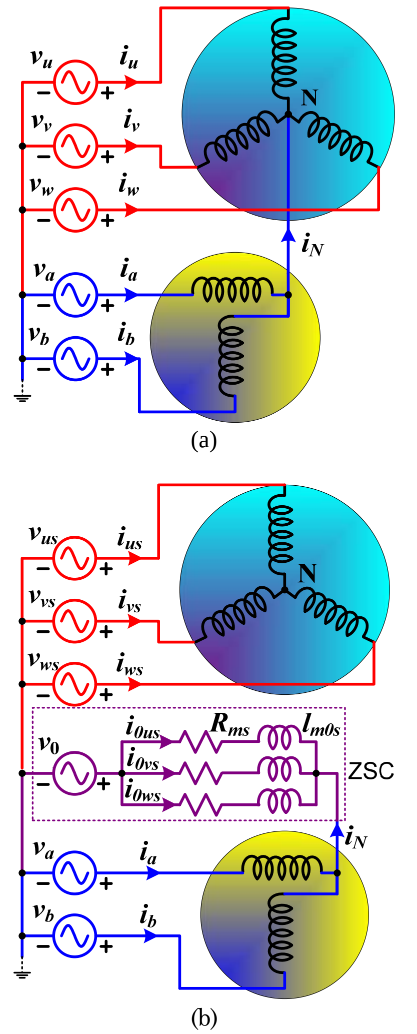


Figure 4. Equivalent circuits; (a) showing inverter phase legs as voltage sources, and (b) showing the zero-sequence circuit of the main motor as the current return path of the two-phase motor.

producing currents of the two motors can be controlled independently.

In Figure 4(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 schemes employed for the three-phase inverter. The zero-sequence voltage (ZSV), v_0, can be calculated by:

$$v_0 = \frac{v_u + v_v + v_w}{3}. \qquad (1)$$

v_{us}, v_{vs}, and v_{ws} are the phase voltages without the zero-sequence component of the three phases, U, V, and W, respectively, and are expressed by

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

The ZSV, v_0, which could be generated by certain PWM strategies such as 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 experimental results.

EFFECT ON THE CURRENT RATING OF THE MAIN MOTOR DUE TO THE TWO-PHASE MOTOR CURRENT

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 to 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 current of the main motor, taking phase-U for example, can be expressed as

$$i_u = i_{us} - \frac{i_a + i_b}{3}, \qquad (3)$$

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

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

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 350.2A, a negligible increase of less than 0.06%.

EXPERIMENTAL VERIFICATION

A prototype, rated 75 kW for the three-phase drive and 5 kW for the two-phase drive, was built and successfully tested with induction motors and permanent maganet synchronous machines. Figure 5 shows a photo of the inverter. Table 1 gives the specifications of the motors. The two-phase induction motor was rewound from a three-phase motor. The two-phase PM motor was

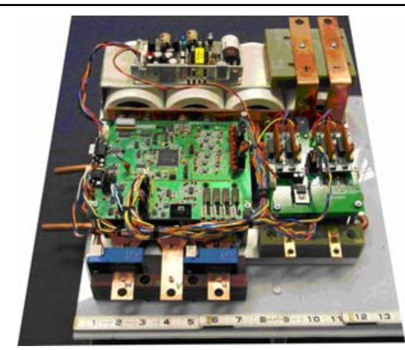
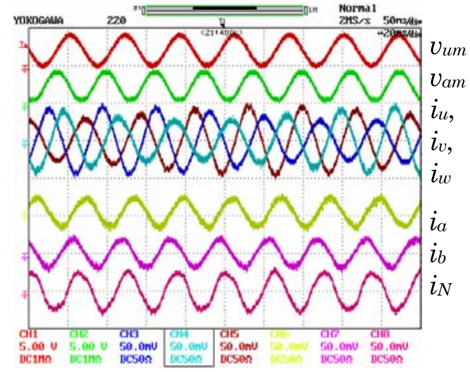


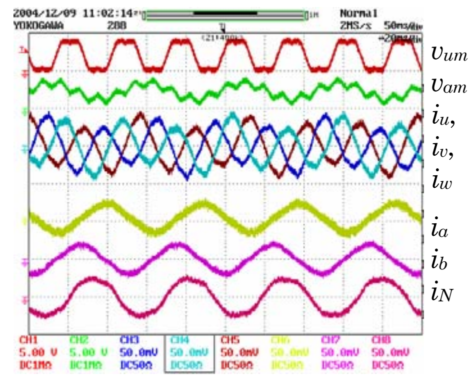
Figure 5. Photo of a 75kW/5kW inverter prototype.

Table 1. Specifications of the motors tested.

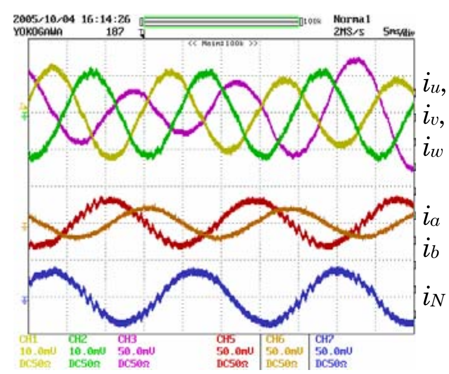
	Induction motors	PM motors
3-phase main motor	15HP/230V/22A, 90N·m, 6-pole	8.2kW/200V/52.7A, 40N·m, 8-pole
2-phase aux. motor	3HP/ 230V/13A, 12.5N·m, 4-pole	5kW/230V/18.9A, 13N·m, 8-pole



(a) Induction motors for v_0=0. Time: 20ms/div.



(b) Induction motors for v_0≠0. Time: 20ms/div.



(c) PM motors. Time: 5 ms/div.

Figure 6. Typical motor current waveforms. Current scale: 50A/div

configured from a three-phase motor by connecting two of the three stator windings in series to form one phase while keeping the remaining stator winding for the other phase. This connection results in an asymmetrical two-phase PM motor of two orthogonal windings with a turns ratio of √3:1. This ratio was maintained between the two phase currents so that the motor will not produce a pulsating torque.

Tests were conducted first with the induction motors and then with the PM machines. Operating conditions varied and included those where only one motor rotated at a time or both spun simultaneously at varying speeds and shaft torques, which verified that the speed of the two motors can be controlled independently. Figure 6 gives typical motor current waveforms, where i_u, i_v, and i_w are main motor currents, i_a, i_b and i_N aux. motor currents, v_{um} and v_{am} are the PWM modulating signals for phase-U and phase-a, respectively. Figures (a) and (b) are for the induction motor test. In (a), the PWM scheme based on sine-triangle comparison was used. The main motor was loaded with 90 N·m at 685 rpm and the two-phase motor with 14.8 N·m at 1100 rpm. In (b), the space vector PWM method was used, and the main motor was loaded with 90 N·m at 690 rpm while the 2-phase motor was loaded with 12.7 N·m at 500rpm. Because the space vector based PWM scheme produces ZSV components, i.e. v_0≠0, the same ZSV components were added to the modulation signals of the two-phase inverter, as can be seen from v_{am}, to prevent them from generating unwanted triple harmonic currents.

Figure 6(c) is taken from the PM machine test under the space vector PWM method, where the main motor was loaded with 40.0 N·m at 1,004 rpm while the auxiliary motor was loaded with 12.0 N·m at 800 rpm. It should be noted that because of the asymmetrical windings of the two-phase motor, its currents, i_a and i_b, are not equal. It should also be noted that the apparent fluctuations of the main motor currents are due to the fact that the rated current of the two-phase motor is comparable to that of the main motor, which will not be the case in intended real application environments.

CONCLUSIONS

The integrated traction and compressor motor drive using a five-leg inverter cuts the component count by more than one-third and thus significantly reduces the cost, size and volume of the compressor motor drive in EV/HEV applications. The experimental results with both induction and ac synchronous PM machines verified that the two motors can operate independently, without interference, identical to operation as if controlled by two separate inverters. In addition, the integration does not increase the current rating of the main inverter switches and the traction motor.

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