Modular PM Motor Drives for Automotive Traction Applications

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Abstract[*] - **This paper presents modular permanent magnet (PM) motor drives for automotive traction applications. A partially modularized drive system consisting of a single PM motor and multiple inverters is described. The motor has multiple three-phase stator winding sets and each winding set is driven with a separate three-phase inverter module. A truly modularized inverter and motor configuration based on an axial-gap PM motor is then introduced, in which identical PM motor modules are mounted on a common shaft and each motor module is powered by a separate inverter module. The advantages of the modular approach for both inverter and motor include: 1) power rating scalability - one design meets different power requirements by simply stacking an adequate number of modules, thus avoiding redesigning and reducing the development cost, 2) increased fault tolerance, and 3) easy repairing. A prototype was constructed by using two inverters and an axial-gap PM motor with two sets of three-phase stator windings, and it is used to assist the diesel engine in a hybrid electric vehicle converted from a Chevrolet Suburban. The effect of different pulse-width-modulation strategies for both motoring and regenerative modes on current control is analyzed. Torque and regenerative control algorithms are implemented with a digital signal processor. Analytical and initial testing results are included in the paper.**

I. Introduction

Most adjustable speed AC drives (ASD) employ a single three-phase induction motor. With such a drive system, the drive has to be shut down if any phase fails. In order to improve reliability of ASD systems, six-phase induction motors fed by double current source inverters have been introduced [1] [2]. Jahns in [3] presents a modular induction motor drive system having multiple independent phases with each phase driven by an independent single-phase inverter. Cengelci in [5] further extends the modular concept into medium voltage three-phase induction motors. Such drives require either a specially wound multiphase motor or reconnecting the windings of a medium voltage induction motor into three-phase winding groups but enable the motor to continue to operate at failure of any single drive unit, although it does degrade motor performance.

This paper presents two modular PM motor drives for automotive traction applications. Compared to induction motors, permanent magnet (PM) motors have higher efficiency due to the elimination of magnetizing current and copper loss in the rotor. It is also easier to achieve high-performance torque control with PM motors, in particular, brushless direct current (BLDC) motors. Owing to these advantages, PM motors have been widely used in a variety of applications in industrial automation and consumer electric appliances. Recent advancements in permanent magnetic materials and motor design have made the PM motor a great candidate for automotive traction drive applications [4][6][7][8][9][10][12].

A modular drive system consisting of a PM motor having multiple three-phase stator winding sets and multiple three-phase inverter modules is first described, in which each winding set is driven separately by one inverter module. A truly modularized inverter and motor drive employing axial-gap PM motors is then introduced, in which identical PM motor modules are mounted on a common shaft and each motor module is powered separately by an inverter module, forming an independent drive unit. The advantages of the modular approach for both inverter and motor include: 1) power rating scalability - one design meets different power requirements by simply employing an adequate number of inverter and motor modules, thus avoiding redesigning and reducing the development cost, 2) increased fault tolerance – failure of any drive unit does not require drive system shutdown, and 3) easy repair by simply replacing the faulted module.

An automotive traction motor drive system was constructed by using two inverter modules and a PM motor with two sets of three-phase stator windings. The PM motor is operated in brushless DC (BLDC) mode. The effect of different pulse-width-modulation strategies for both motoring and regenerative modes on current control is analyzed. Torque and regenerative control algorithms are implemented with a digital signal processor. The drive system is used to assist a hybrid electric vehicle converted from a Chevrolet Suburban to increase its fuel economy and to reduce its emissions. Analytical and initial testing results are included in the paper.

II. Modular Drive System Configurations

A modular motor drive can be constructed by using

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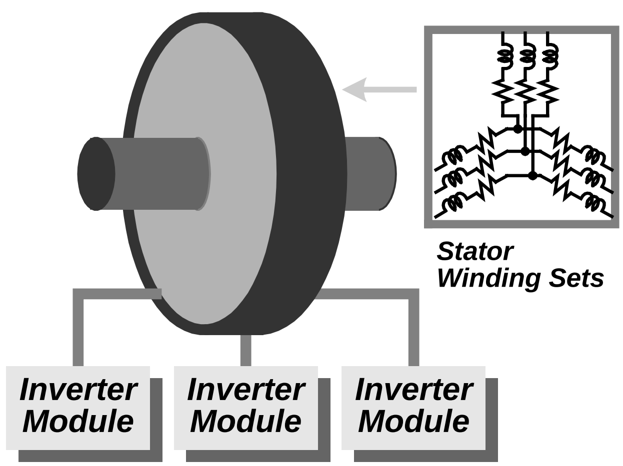
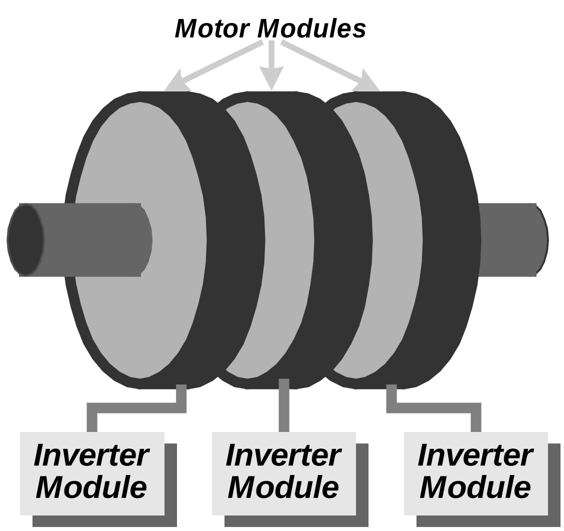
multiple sets of stator windings with a single rotor and by powering each set with a separate inverter, as shown in Fig. 1(a). To take advantage of the modular inverter configuration, the stator windings are arranged into multiple three-phase sets rather than a single multi-phase configuration. A true modular design can be constructed with axial-gap PM motors. Each motor module has its own stator and rotor and all modules are mounted on a common shaft, as shown in Fig. 1(b). Moreover, each motor module is driven by a separate inverter module, forming an independent drive unit. The inverter modules can share a common DC power source to reduce cost or can have a separate DC source to increase the level of fault tolerance. Once the inverter and motor modules are developed, an adequate number of the modules can be stacked together to meet the power rating requirement in specific applications, thus leading to significant development cost savings compared to the approach that employs specific designs for specific applications. The drive system may continue to operate as long as not all of the drive units fail, albeit at reduced power. This may be important for certain applications that require a high level of fault tolerance as in EV/HEV applications.



(a) Modular inverter and multiple (three) stator winding sets



(b) Modular inverter and modular motor

Fig. 1. Modular inverter and modular motor drive system configurations.

Rotor position information is required to properly control a PM motor and may be provided by position sensors such as an optical encoder or Hall-effect probes. In certain situations where the inverter is not required to start the motor, position sensorless schemes may be employed to eliminate the position sensors [11]. Again, one can either employ one set of position sensors for all of the drive units to reduce cost or equip each drive unit with its own position sensor to increase the drive system reliability.

There are mainly two ways to excite a PM motor. One is to drive the motor in synchronous AC mode in which a three-phase sinusoidal current is delivered to a motor that has a sinusoidal back EMF. The other excitation scheme, which has been proved particularly attractive for high power drive systems and is thus the choice for the prototype traction motor drive described in this paper, is for BLDC motors. It consists of a three-phase PM motor with a trapezoidal back EMF excited by quasi-square current waveforms. This excitation can be conveniently accomplished with a three-phase full-bridge voltage source inverter. Synchronous PM motors require constant supply of rotor position information and as such a pulse encoder of high resolution or a resolver is usually used. In contrast, a controller for BLDC motors needs knowledge of only six points of the rotor position per a fundamental electrical cycle and low cost sensors such as Hall-effect probes can be used.

As an additional benefit, torque ripple on the shaft of a modular drive can be reduced for both configurations by introducing a phase shift of 360/*n* degree into the PWM carriers for the *n* modular inverters so that low order torque ripples contributed by each module are cancelled out. Alternatively, a lower PWM carrier frequency can be employed for a given level of torque ripple. For BLDC motors in the second configuration, the torque pulsation resulting from phase commutation can also be pushed into higher frequency by properly mounting the motor modules on the shaft with angular displacement of rotor poles so that phase commutation of the motor modules does not occur at the same time. The frequency of the torque pulsation can be raised to $n \times 6 \times p \times N_{RPS}$ for a drive system consisting of n modules with each having a pole pair number of p, and rotating at N_{RPS} revolution per second.

III. PULSE WIDTH MODULATION STRATEGIES FOR BLDC MOTOR

While both synchronous and brushless PM motors can be used for the modular motor drive, a brushless PM motor is adopted for the prototype because of its relative ease of control and low cost. The effect of different pulse-width-modulation (PWM) strategies for both motoring and regenerative modes on current control is analyzed.

Fig. 2 shows one drive module and two PWM strategies for current control in motoring mode, where a three-phase full-bridge voltage source inverter is employed. The PM motor is represented by an equivalent circuit consisting of a stator resistance, inductance and back EMF connected in series for each of the three phases with the mechanical moving portion omitted, where e_a, e_b and e_c are phase back EMFs. The figure also shows phase-*a* ideal stator current that the inverter should provide and its relationship with the back EMFs. The currents in each phase have a rectangular wave-shape and must be in phase with the back EMFs of the corresponding phase. PM motors tend to have low inductance. While a low inductance helps in producing a closer-to-desired rectangular current waveform, it also unfortunately generates larger current ripples for a given switching frequency of the inverter. To reach an optimum design, all factors including switching loss and extra loss generated from current ripple and current control response must be evaluated. One added feature of the modular drive is that one can increase the frequency of torque ripple by introducing a phase shift into the PWM carriers of each drive unit as mentioned in section II.

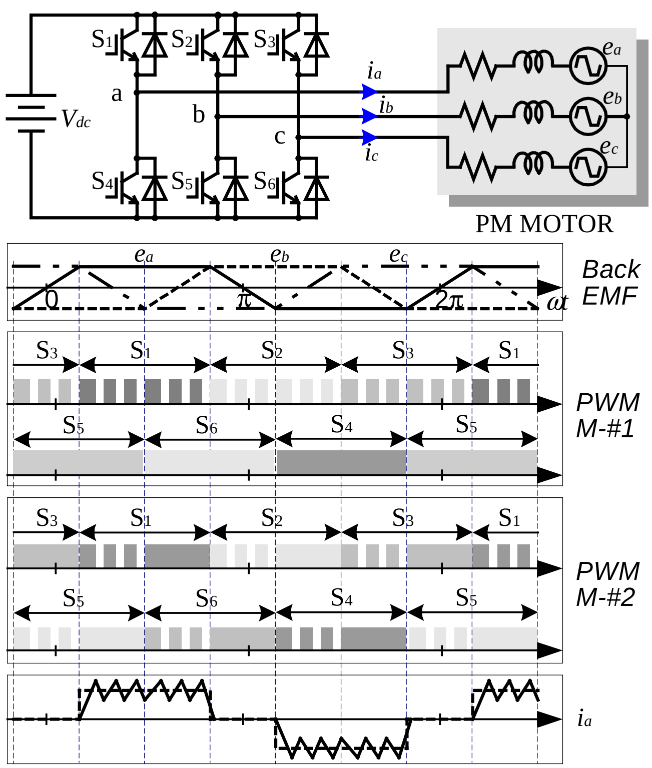
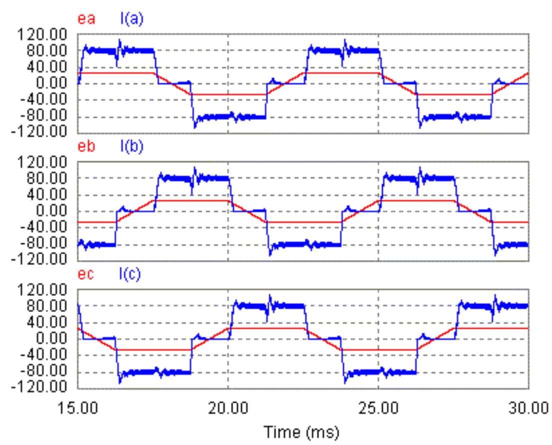


Fig. 2 PWM strategies for current control in motoring mode.

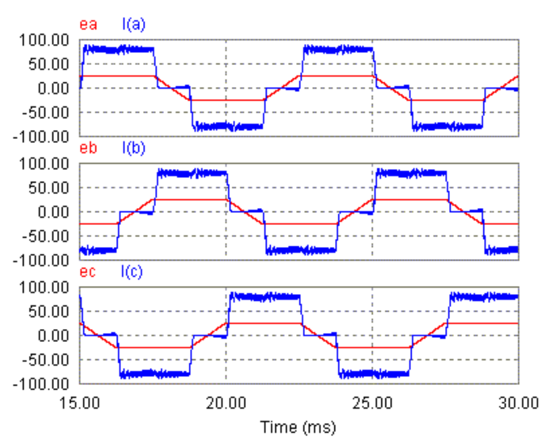
For PWM strategy M-#1, only the upper three switches of the inverter phase legs perform pulse-width-modulation to regulate the motor current, while the bottom switch of a given phase leg keeps conducting for 120 electrical degrees corresponding to the negative flat segment of that phase back EMF, as illustrated in Fig. 2. Alternatively, one can implement this strategy by putting the lower three switches into PWM mode while keeping the upper switches conducting for their respective 120 degrees. In strategy M-#2, PWM operation is rotated among the six switches synchronized with the back EMFs. Each switch begins PWM for the first 60 electrical degrees and then keeps conducting for another 60 electrical degrees. Again, one can implement this strategy by letting each switch conduct for the first 60 degrees and then doing PWM for the rest of the 120 degrees. However, doing PWM for the second part of the 120 degrees has an adverse effect on the current waveforms as with the strategy M-#1. Another possible PWM scheme is to let both the upper and lower conducting switches do PWM simultaneously. This, however, produces higher current ripples.

Compared to PWM strategy M-#2, PWM strategy M-#1 is easy to implement but has the following disadvantages.

- The three devices performing PWM bear higher heat stress than the other three because of their switching loss,
- At the commutation between the lower switches the rising rate of the incoming phase current can not match the decaying rate of the outgoing phase current, producing an adverse effect on the motor current waveform, as will be shown in the following simulation results.



(a) for PWM M-#1.



(b) for PWM M-#2.

Fig. 3 Simulation waveforms with different PWM strategies for motoring mode.

Fig. 3 shows a comparison of typical simulation waveforms generated by the two PWM strategies, where *I(a)*, *I(b)* and *I(c)* are the three phase currents, and *ea*, *eb* and *ec* represent the three phase back EMFs (trapezoidal waveform). It can be seen that strategy M-#1 produces an oscillation at the middle of the positive half cycles of current waveform, which is caused by the fact that the decaying rate of outgoing phase current is faster than the rising rate of incoming phase current at the commutation between the lower switches. This is not the case for the modulation strategy M-#2 and thus it produces smaller disturbances to the conducting phase current at the instants of switch commutation.

There are also several possible PWM strategies for regenerative power control. Two of them are illustrated in Fig. 4. For the PWM R-#1, the lower switch of each phase leg performs pulse width modulation during the time period corresponding to the positive 120 degree flat top of the phase back EMF. With strategy R-#2, the modulation period of each switch extends to 180 degrees. There is an overlap period of 60 degrees between two consecutive modulations, which is employed to improve the current waveform, as will be seen in the following simulation results. For both the PWM schemes, the bypass diodes allow all three upper switches to remain off. Two other possible strategies, for which all three switches perform PWM simultaneously or each switch does PWM during the entire positive half cycle of the corresponding phase back EMF, will produce essentially the same current waveform as PWM R-#2. It is also obvious that one can reverse the roles of the upper and lower switches by keeping the lower switches off but controlling the upper switches with PWM. Further, one can rotate the part doing PWM among the lower and upper switches to distribute the switching loss and the resultant heat among the switches.

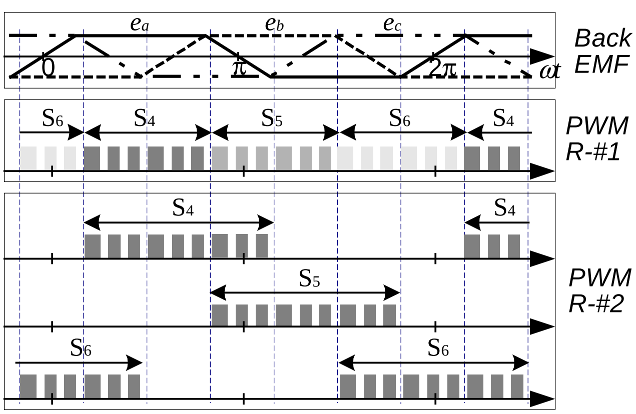
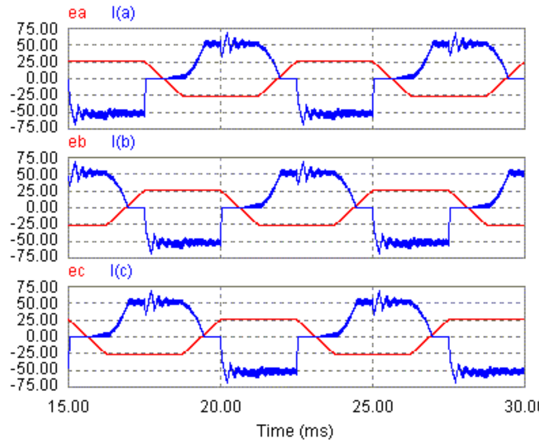
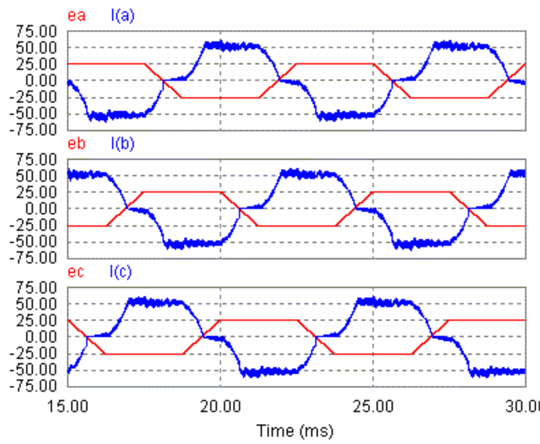


Fig. 4 PWM strategies for current control in regenerative mode.

Fig. 5 shows a comparison of typical simulation waveforms generated by the two PWM strategies, where *I(a)*, *I(b)* and *I(c)* are three phase currents, and *ea*, *eb* and *ec* represent the three phase back EMFs. It can be seen that the strategy R-#1 produces an asymmetrical current waveform with a noticeable oscillation at the commutation instants. In contrast, the strategy R-#2 yields a symmetrical current waveform without a noticeable oscillation at commutation instants. The following observations can be made. Although PWM strategy R-#1 produces less switching loss since only one switch does PWM at a time, it may generate larger di/dt noise due to the sharp change in the current waveform at commutation instants. In contrast, PWM strategy R-#2 produces larger switching loss because there is an overlap of 60 degrees when two switches perform PWM, but it generates lower di/dt noise due to the slow change in the current waveform, as shown in Fig. 5(b).



(a) for PWM R-#1.



(b) for PWM R-#2.

Fig. 5 Simulation waveforms with different PWM strategies for regenerative mode.

IV. PROTOTYPE AND EXPERIMENTAL RESULTS

A prototype traction drive system was built based on the modular design for a hybrid electric vehicle. The HEV is converted from a Chevrolet Suburban and a photo of the vehicle is shown in Fig. 6. An electric-assist parallel-hybrid strategy is employed to convert the vehicle. A 2.4-liter turbo diesel engine is used as the main power plant with the axial gap PM motor to assist during heavy loading. Fig. 7 illustrates the drivetrain configuration. A shaft couples the engine to the transmission by passing through the motor. The engine drives through the motor to the transmission, allowing the motor to boost the torque on the shaft. The engine always runs preventing the vehicle from being zero emission capable, but the motor can assist or even dominate the power supplied to the transmission thus reducing the overall loading on the engine. This creates a power-train which is superior to the stock Suburban in fuel economy and maximum power.

Fig. 8 depicts the motor drive system configuration, in which two modular inverters are employed to drive the axial gap PM motor with two sets of three-phase stator coils; each inverter separately powers one set of stator coils and the two inverter-modules share a common DC power source provided by a string of batteries. Each inverter module uses a standard bridge inverter power circuit provided by a six-pack intelligent IGBT module and is rated at 15 kW continuous power with a peak power of 45 kW for a short period of time. A voltage sensor is also used to monitor the DC bus battery voltage. The PWM strategies discussed above were tested.

Fig. 6 Photo of the experimental HEV.

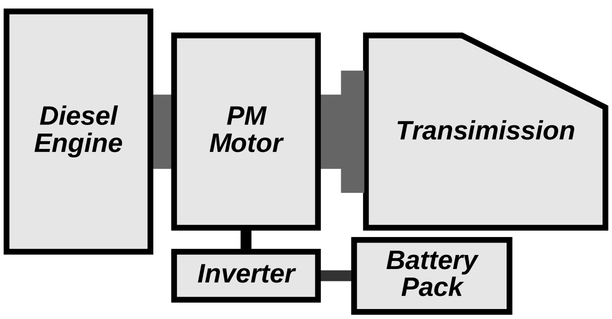


Fig. 7 Drivetrain configuration.

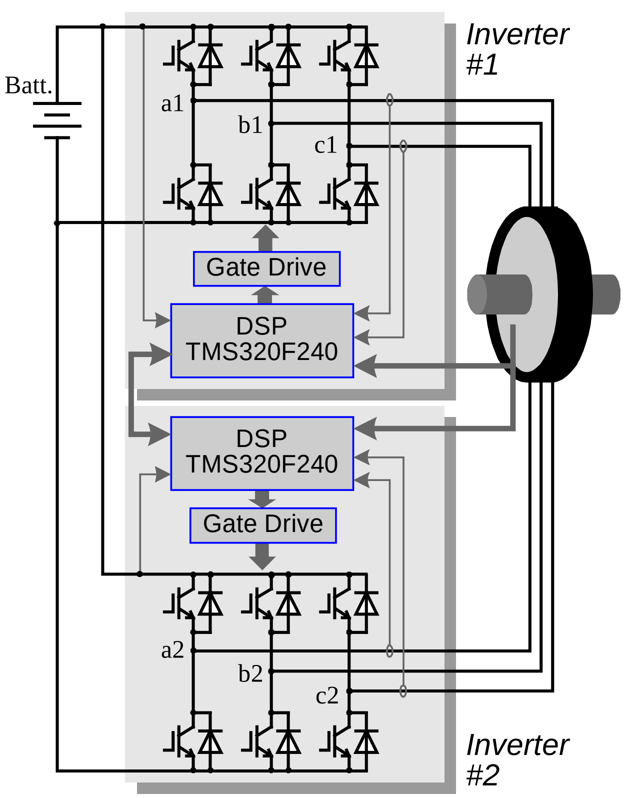
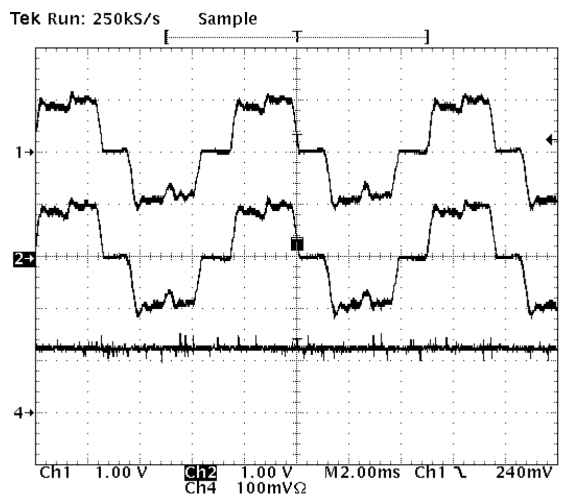
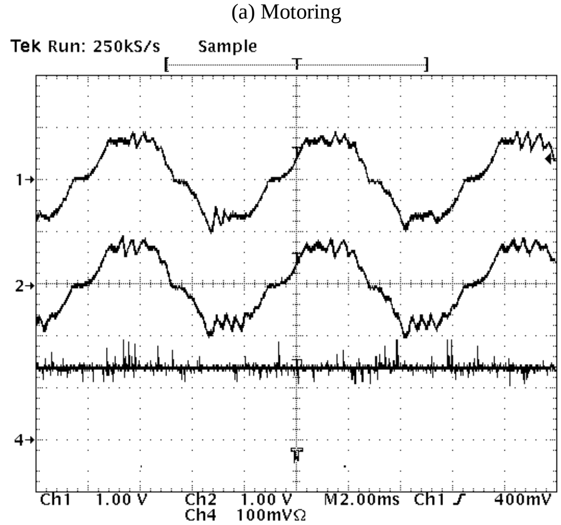


Fig. 8 Traction motor drive configuration based on the modular design.

The motor has a maximum speed of 4000 rpm and is operated in BLDC mode. Torque and regeneration control algorithms for HEV applications are implemented with a digital signal processor, TMS320F240 of Texas Instruments, which is specifically designed for motor control [13]. It contains all the hardware needed for motor control such as PWM modulators capable of the most commonly used carrier based or space vector PWM, capture/encoder input interface including necessary counters, and A/D converters of eight channels. The position signals from a set of Hall effect probes are fed to both DSPs through their capture inputs. The DSP also provides a Master/Slave high-speed synchronous port, which may be used to implement a communication link between the inverter modules, if necessary. The use of the DSPs and an intelligent IGBT module, which includes pre-drives and protection logic necessary for safe inverter operation, greatly reduces part count, and results in a compact inverter package.



(a) Motoring

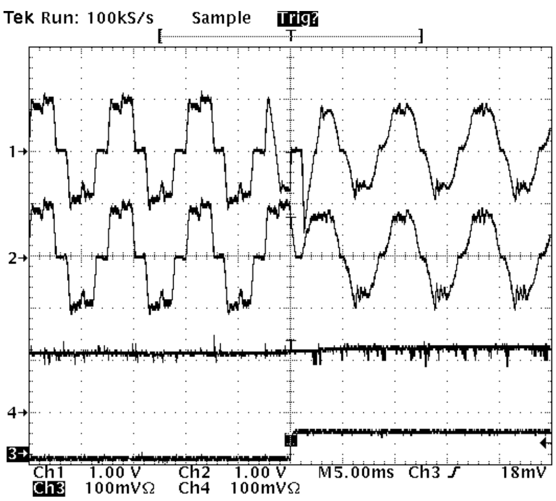


(b) Regeneration

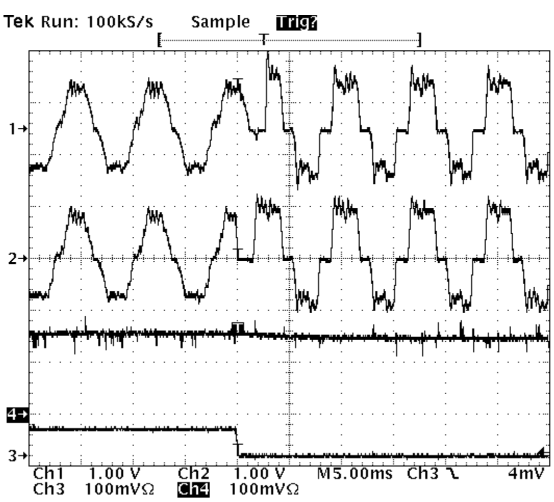
Fig. 9 Steady state waveforms at 1000 rpm. 1: Phase C current of inverter #1, 100 A/div; 2: Phase C current of inverter #2, 100 A/div; 4: DC bus voltage, 200 V/div; Time: 2 ms/div.

The drive system was thoroughly tested for both motoring and regenerative modes with a dynamometer. Fig. 9 shows typical current and DC bus voltage waveforms of both inverters in steady states, where (a) is in the motoring mode and (b) is in the regeneration mode. It clearly indicates that the two inverters are operating in a perfectly synchronized manner.

Fig. 10 shows typical current and DC bus voltage waveforms of both inverters in transient states, where (a) shows a transition from motoring to regeneration and (b) a transition from regeneration back to motoring. Successful operation of mode transition can be observed by the increase in the DC bus voltage as the inverter is switched from motoring to regeneration and by the decrease in the DC bus voltage as the inverter is switched from regeneration back to motoring mode.



(a) Transition from motoring to regeneration



(b) Transition from regeneration to motoring

Fig. 10 Transient state waveforms at 1000 rpm. 1: Phase C current of inverter #1, 100 A/div; 2: Phase C current of inverter #2, 100 A/div; 4: DC bus voltage, 200 V/div; 3: mode transition command; Time: 5 ms/div.

After extensive testing on the dynamometer, the motor drive system has been installed into the vehicle. Initial road testing looks promising. Data are being collected to evaluate improvement on acceleration, fuel economy, emissions and other vehicle performances.

V. CONCLUSIONS

Modular configurations of both an inverter and/or PM motor are described for adjustable speed drives in automotive traction applications. The modular approach can significantly reduce the development time and cost due to the power rating scalability and can increase the level of fault tolerance. The effect of various PWM strategies on current control is analyzed. It is shown that PWM strategies M-#2 and R-#2 yield the best results for motoring and regenerative control, respectively. Experimental results have demonstrated successful operation of a PM BLDC drive employing the modular design for hybrid electric vehicle applications.

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