

Design of a PM Brushless Motor Drive for Hybrid Electrical Vehicle Application

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ABSTRACT*

This paper describes a modular design of axial gap permanent magnet (PM) motor drives, in which identical PM motor modules are mounted on a common shaft and each motor module is powered separately by an inverter module. The advantages of the modular design approach for both inverter and motor include: 1) power rating scalability - one design meets different power requirements by simply increasing or decreasing the number of modules, thus avoiding redesigning and reducing the development cost, 2) increased fault tolerance, and 3) easy repairing. An automotive traction motor drive system was constructed by using two modular inverters and a PM motor with two sets of three-phase stator coils. Each inverter separately drives a set of stator coils. The PM motor is operated in brushless DC 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 repower a hybrid electric vehicle converted from a Chevrolet Suburban to increase its fuel economy substantially. Analytical and initial testing results are included in the paper.

1. 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]. Further Jahns in [3] presents an extensive investigation of an induction motor drive system having multiple independent phases with each phase driven by an independent single-phase inverter. Such a drive requires a specially wound multiphase motor but enables the motor to continue to operate at failure of any single drive unit, although it does degrade motor performance.

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

* Research sponsored by Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Dept. of Energy under contract DE-AC05-00OR22725.

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motor design have made the PM motor a great candidate for traction drives in electric and hybrid electric vehicle applications [4][5][6][7][8][9].

This paper presents a true modular motor drive employing axial gap permanent magnet (PM) motors, 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 design approach for both inverter and motor include: 1) power rating scalability - one design meets different power requirements by simply increasing or decreasing the 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 modular inverters and a PM motor with two sets of three-phase stator coils. Each inverter separately drives a set of stator coils. The PM motor is operated in brushless DC 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 repower a hybrid electric vehicle converted from a Chevrolet Suburban to increase its fuel economy substantially. Analytical and initial testing results are included in the paper.

2. MODULAR DRIVE SYSTEM CONFIGURATION

Although a modular motor drive can be constructed by using multiple sets of stator windings with a single rotor, a true modular design can be realized 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. Each motor module is powered 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 them can be stacked together to meet the power rating requirement of specific applications, thus leading to significant development cost savings compared to the approach that employs specific designs for specific applications. The drive system can 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. As is well known, rotor position information is required to properly control a PM motor and can 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 sensor-less schemes may be employed to eliminate the position sensors. 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 traction motor drive, 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. An attractive feature of this approach is the resulting simplicity of inverter phase commutation. The flat top of the trapezoidal back EMF waveform is well matched to the quasi-square wave current waveform that can be produced by a voltage source inverter, lending itself to a low cost drive system. One disadvantage of the trapezoidal back EMF waveform is the requirement for accurate stator current commutation control. The torque developed in a PM motor with a trapezoidal back EMF is very sensitive to the relative phase of the quasi-square wave currents imposed by the inverter with respect to the back EMFs. A small phase error in

commutation can produce significant pulsating torque in such drives. Accurate phase information of the back EMF is thus required to properly commute the stator currents with an inverter.

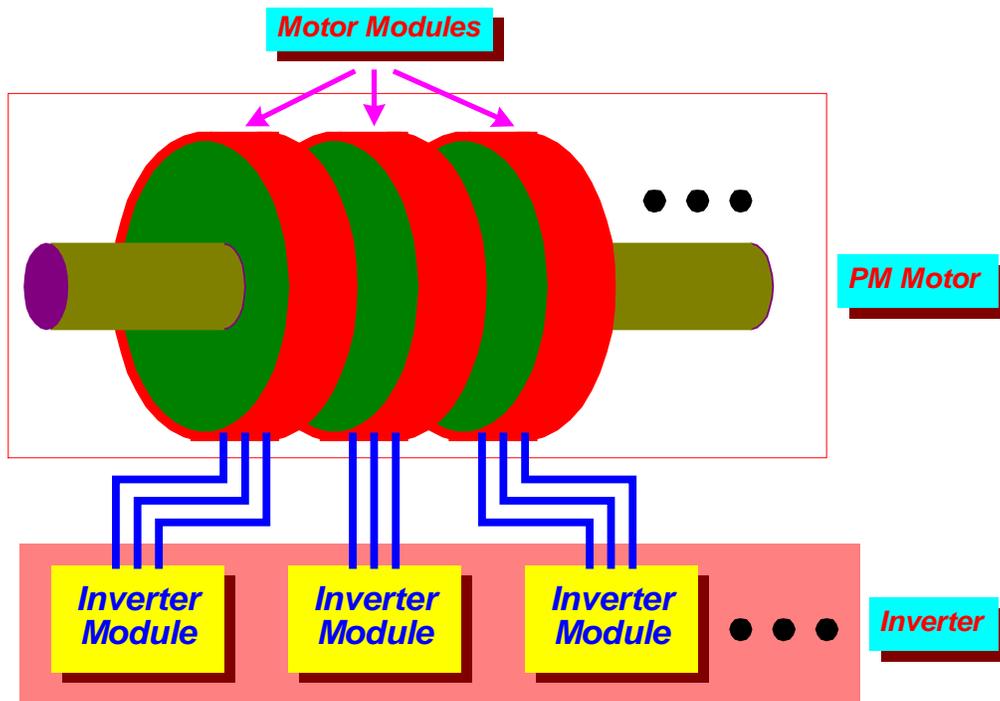


Fig. 1. Modular inverter and modular motor drive system configuration.

3. PULSE WIDTH MODULATION STRATEGIES

While both synchronous and brushless PM motors can be used for the modular motor drive, a brushless PM motor is adopted for 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 two PWM strategies for current control with a three-phase full-bridge voltage source inverter in motoring mode. 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 the ideal stator currents that the inverter should provide and their 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. In this way the flat top of the trapezoidal back EMF waveform is well matched to the quasi-square wave current waveform that can be produced by a voltage source inverter, lending itself to a low cost drive system. Such ideal currents will develop a constant power, and thus torque, delivered to the rotor. Because of the nonzero inductance of the state phase windings, the resulting actual phase currents will be unable to assume the desired quasi-square waveform. Instead, the currents are trapezoidal due to the finite rise and fall time, and contain ripples due to the limited switching frequency of the inverter. This affects the torque production and drive performance. While a low inductance motor produces a closer-to-desired rectangular current waveform, it also unfortunately generates larger current ripples for a given switching frequency of the inverter. To reduce the current ripple, a higher switching frequency is required, which in turn produces higher switching loss. To reach an optimum design, all factors must be evaluated, which include switching loss and extra loss generated from current ripple and

current control response. 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.

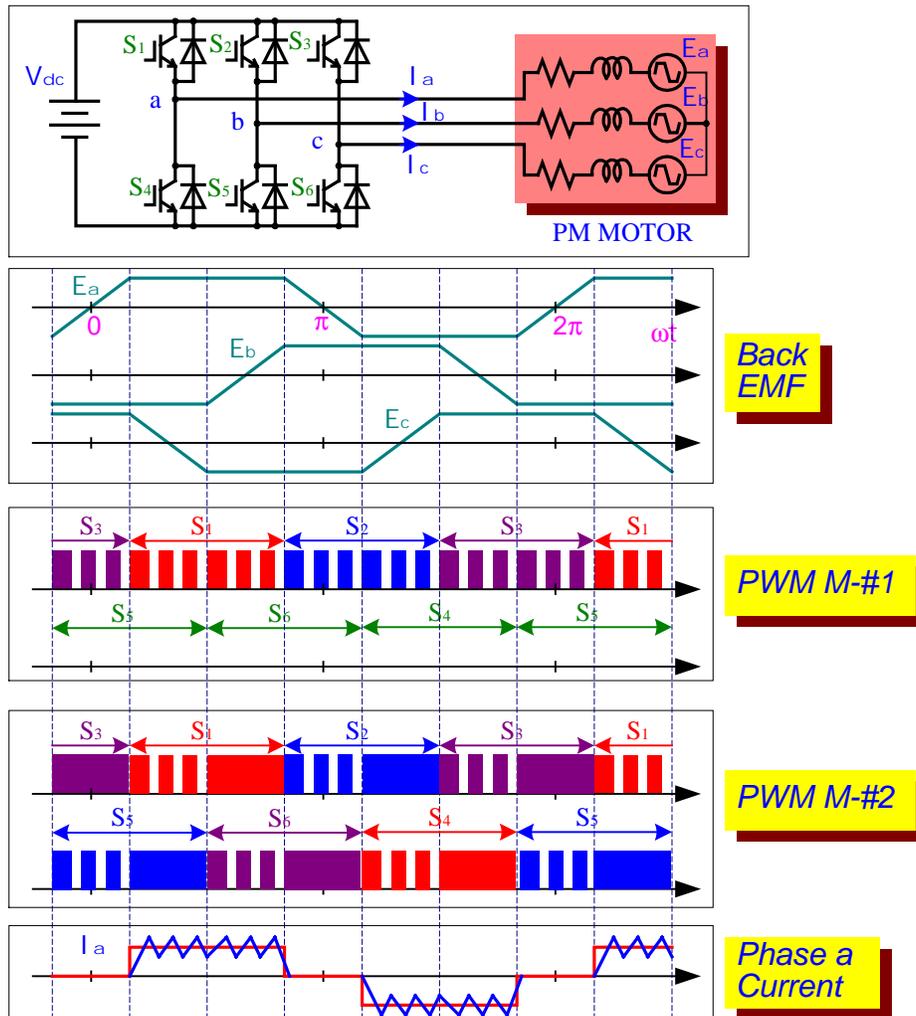


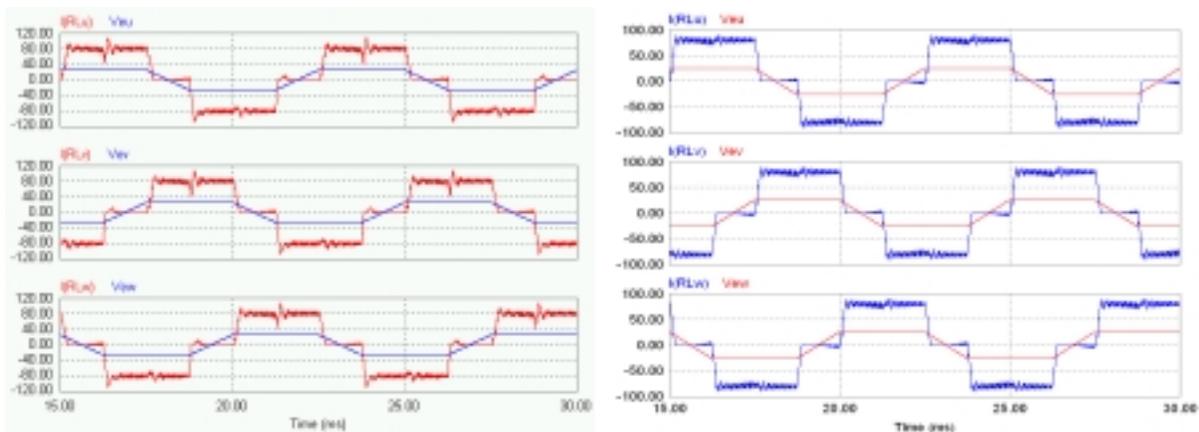
Fig. 2 PWM strategies for current control in motoring mode.

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 the phase back EMF. 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 conducting 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 doing PWM simultaneously. It, 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 simulation results.

Fig. 3 shows a comparison of typical simulation waveforms generated by the two PWM strategies, where $I(RL_u)$, $I(RL_v)$ and $I(RL_w)$ are the three phase currents, and V_{eu} , V_{ev} and V_{ew} represent the three phase back EMFs. 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.



(a) for PWM M-#1.

(b) for PWM M-#2.

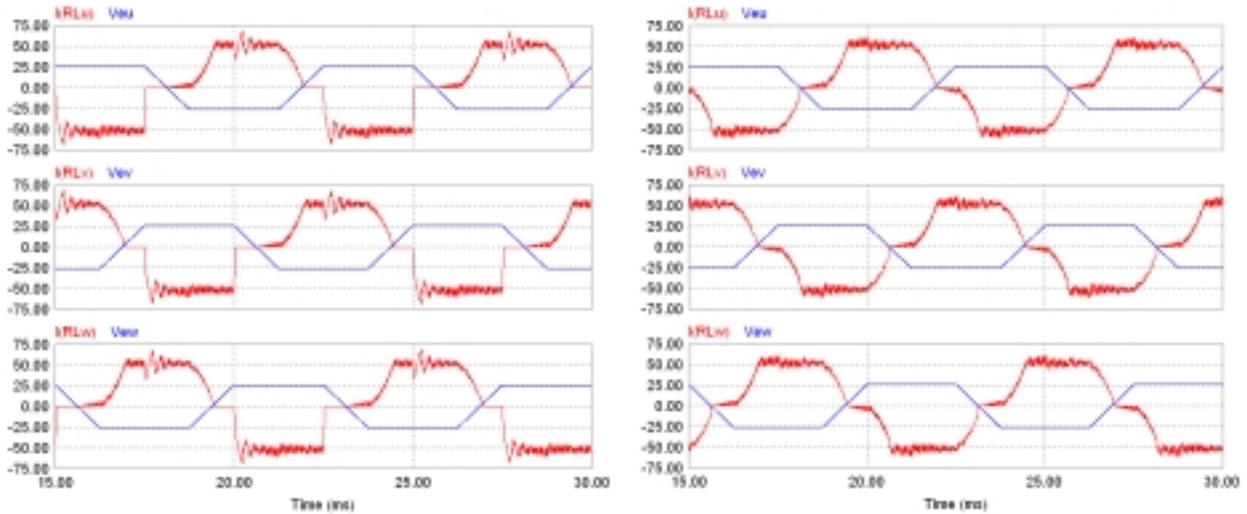
Fig. 3 Simulation waveforms with different PWM strategies for motoring mode.

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 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 $I(RL_u)$, $I(RL_v)$ and $I(RL_w)$ are three phase currents, and V_{eu} , V_{ev} and V_{ew} represents the three phase back EMFs. It can be seen that the strategy R-#1 produces an asymmetrical current waveform with a noticeable oscillation at 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.

4. EXPERIMENTAL RESULTS

A prototype traction drive system is built based on the modular design to repower a hybrid electric vehicle converted from a Chevrolet Suburban. Fig. 6 shows the traction drive system configuration, in which two modular inverters are employed to drive an 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. PWM strategies discussed before were tested.

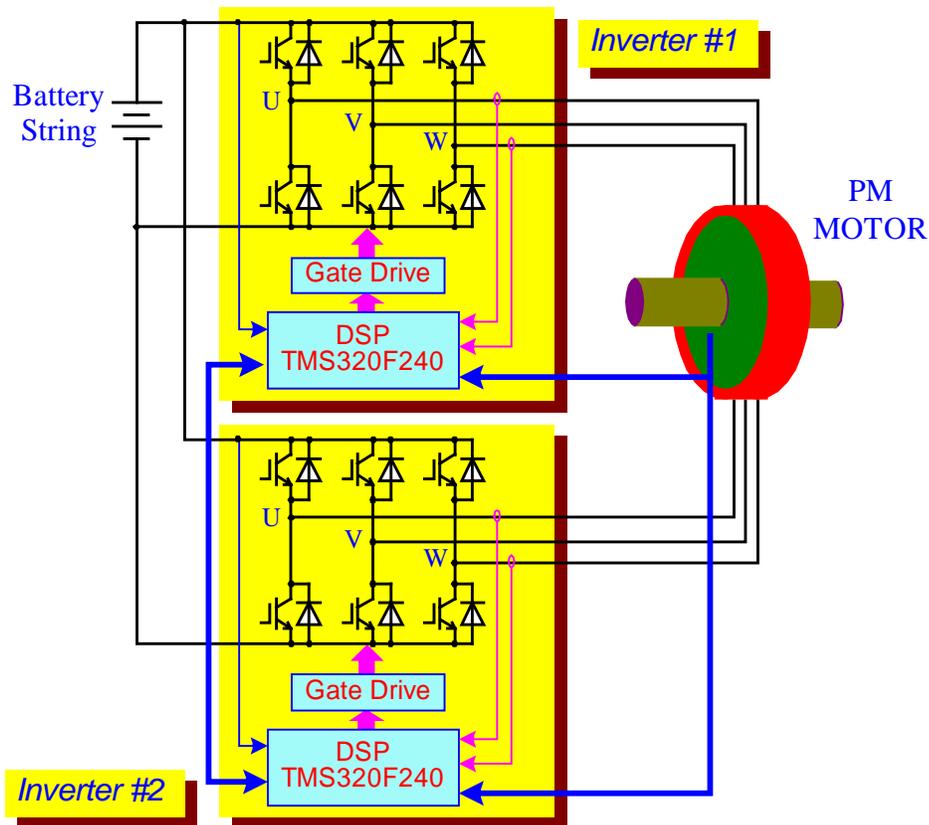


Fig. 6 A prototype of traction drive configuration based on the modular design.

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. The DSP chip used in this development is TMS320F240 of Texas Instruments, which is specifically designed for motor control [10]. 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 is used for RS-485 based communications to provide a synchronization mechanism between the inverter modules. 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.

The drive system was thoroughly tested for both motoring and regenerative modes with a dynamometer. Fig. 7 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.

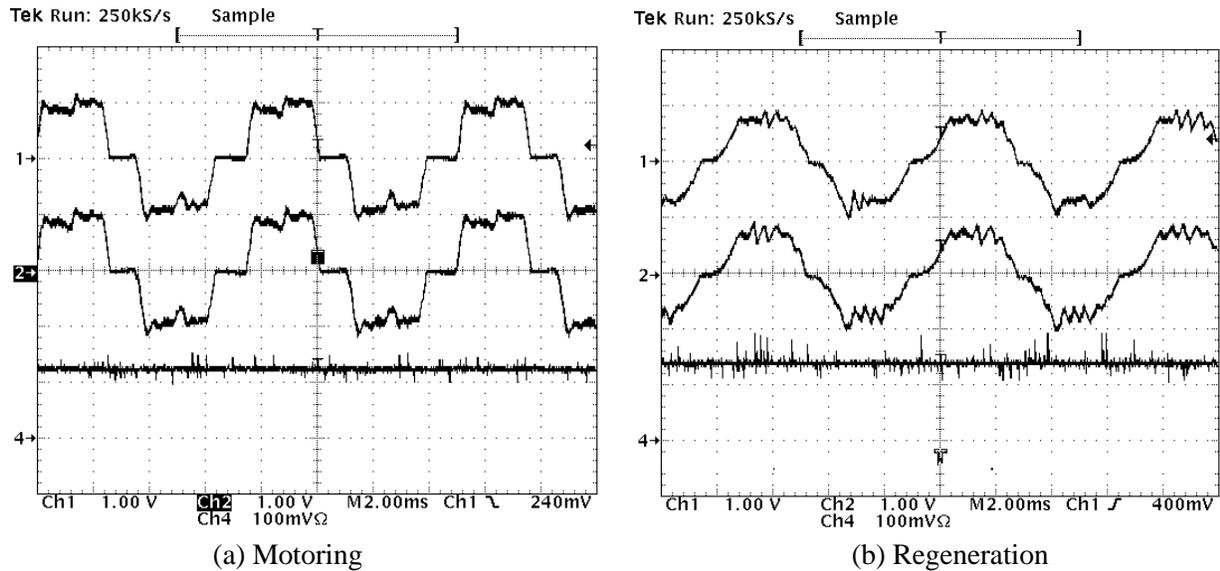


Fig. 7 Steady state waveforms at 1000 rpm. 1: Phase C current of inverter #1, 100 A/div; 2: Phase C current of inverter #2, 100 A/div; 4: DC bus voltage, 200 V/div; Time: 2 ms/div.

Fig. 8 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.

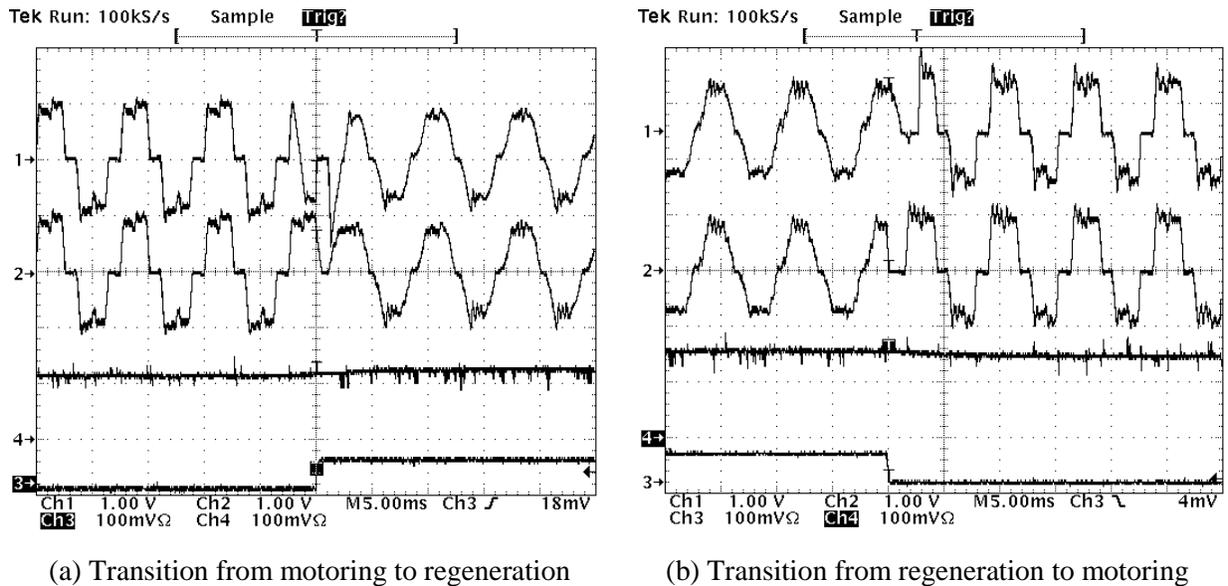


Fig. 8 Transient state waveforms at 1000 rpm. 1: Phase C current of inverter #1, 100 A/div; 2: Phase C current of inverter #2, 100 A/div; 4: DC bus voltage, 200 V/div; 3: mode transition command; Time: 5 ms/div.

5. CONCLUSIONS

A modular design of both inverter and PM motor is described for adjustable speed drives. The modular approach can significantly reduce the development time and cost due to the power rating scalability and 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.

ACKNOWLEDGEMENT

The authors are grateful to Craig Rutherford and Jiann-Long Wu for their assistance in the prototype assembly and testing.

REFERENCES

- [1] E. A. Klingshirn, "High Phase Order Induction Motors, Part II – Experimental Results," *IEEE Trans., Power App. Syst.*, vol. PAS-102, pp. 54-59, Jan. 1983.
- [2] M. A. Abbas et al., "Six-Phase Voltage Source Inverter Driven Induction Motor," *IEEE Trans. Ind. Applicat.*, vol. IA-20, pp. 1251-1259, Sep./Oct. 1984.
- [3] T. M. Jahns, "Improved Reliability in Solid-state AC Drives by Means of Multiple Independent Phase Driven Units," *IEEE Trans. Ind. Applicat.*, vol. IA-16, pp. 321-331, May/June 1980
- [4] D. M. Erdman, H. B. Harms, J.L. Oldenkamp, "Electronically Commutated DC Motors for the Appliance Industry," *Conf. Rec. 1984 IEEE Ind. Applicat. Soc. Ann. Mtg.*, pp. 1339-1345.
- [5] M. Lajoie-Mazenc, C. Villanueva, J. Hector, "Study and Implementation of Hysteresis Controlled Inverter on a Permanent Magnet Synchronous Machine," *Conf. Rec. 1984 IEEE Ind. Applicat. Soc. Ann. Mtg.*, pp. 426-430.
- [6] C. Bergmann, P. Goreau, J.P. Louis, "Direct Digital Control of a Self-Controlled Synchronous Motor with Permanent Magnet," *1st European Conf. on Power Electronics and Applications*, pp. 3.269-3.273, Oct. 1985.
- [7] A. Kusko, S. M. Peeran, "Brushless DC Motors Using Unsymmetrical Field Magnetization," *Conf. Rec. 1986 IEEE Ind. Applicat. Soc. Ann. Mtg.*, pp. 774-780.
- [8] B. V. Murty, "Fast Response Reversible Brushless DC Drive with Regenerative Breaking," *Conf. Rec. 1984 IEEE Ind. Applicat. Soc. Ann. Mtg.*, pp. 445-450.
- [9] G.J. Su, G. W. Ott, J. W. McKeever, K. S. Samons, R. L. Kessinger, "Development of a Sensor-less Speed Control Inverter for an Automotive Accessory Permanent Magnet Motor", *2000 Future Car Congress*, April 2000.
- [10] "TMS320C24x DSP Controllers Reference Set," Texas Instruments, 1997.