Development of BLDC Motor Drive for Automotive Applications

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Abstract*- In order to save resources and prevent global warming, there has been a pressing need in recent years to reduce the volume of CO2 emissions, and to improve the fuel consumption of automobiles. Due to environmental concerns, the recent regulation on automobile fuel economy has been strengthened. The market demand for efficient vehicles is growing and automakers to improve engine fuel efficiency in the industry have been paying a lot of effort. Under these circumstances, the mechanical parts in the automobile industry are being replaced by electronic methods. In this paper, authors introduce two methods. First method is water pump. Especially, to improve vehicle engine efficiency, power transmission and around the field of devices according to driving conditions need to be properly cooled. Conventional mechanical water pump is directly connected by the engine belt. For this reason, regardless of coolant circulation, the conventional mechanical water pump is always operated. However, the electric water pump can be operated only when needed through the proper motor speed control. The way which the mechanical water pump is replaced by electric water pump could reduce energy consumption. Second method is VVA(Variable Valve Actuation) technology. To improve the fuel efficiency, it is necessary to reduce losses or to improve combustion efficiency of the engine. VVA technology enhances the engine's intake air flow, reduce pumping losses and mechanical friction losses. And also, VVA technology is the engine's low speed and high speed operation to implement each of appropriate valve lift. It improves the performance of engine in the entire operating range. This paper presents a design procedure of drive for water pump and VVA system and shows the validity of the result by experimental result with prototype.

I. INTRODUCTION

Due to the recent environmental problems, the automobile fuel economy regulations have been strengthened around the world, and market demands for higher fuel efficiency in vehicles is increasing. In order to improve fuel efficiency, the automobile industry has been devoting a lot of effort. To improve the fuel efficiency, it is needed to improve the efficiency of the vehicle and reduce losses. Under these circumstances, the mechanical parts in the automobile industry are being replaced by electronic methods. For high efficiency, there are lots of methods. VVA and the water pump is one of them. These two technologies are very different. However, they locate around engine and have similar temperature range and current capacity.

Conventional mechanical water pump is directly connected by the engine belt. For this reason, regardless of coolant circulation, the conventional mechanical water pump is always operated. In contrast, electric water pump is not directly connected and could operate at various speeds using inverter drive system. The way which the mechanical water pump is replaced by electric water pump could reduce energy consumption. For this possible, integrated electric water pump is becoming more important.

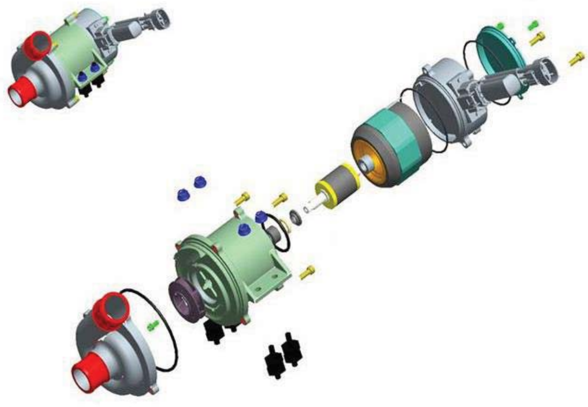

Fig. 1. Automotive water pump structure.

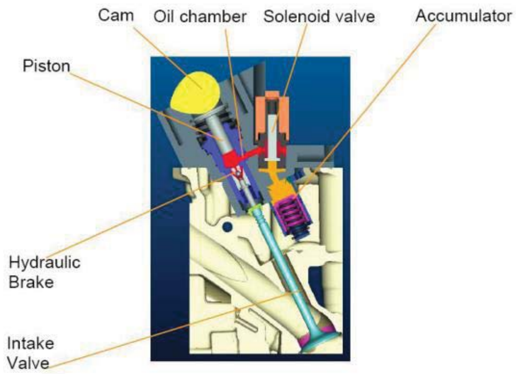

Fig.2. VVA system [8].

VVA technologies enhance the flow of the engine intake, reduce pumping losses and mechanical friction losses. Through this technology, the engine could improve fuel economy. VVA technology is also driving the engine's low speed and high-speed operation to implement each of the valve lift is appropriate. In all operating regions, it improves engine performance. The vehicles by optimizing the gear ratio could improve fuel economy.

DC motors have ever been prominent in various industrial applications because their characteristics and controls are

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simple. In an industrial point of view, the dc motor is still more than others at low power ratings. However, dc motor drives have bulky construction, low efficiency, low reliability and need of maintenance. Those features are unsuitable for automotive applications [1]-[2].

In recent years, the brushless dc (BLDC) motor is receiving more interest for automotive applications. This is due to the total elimination of the brush/commutator assembly, which reduces audible noise and RFI problems. Moreover, BLDC motor has a number of advantages such as high efficiency, high power factor, and low maintenance cost [1]-[6]. The motor for automotive application should be made compact and increasing the efficiency causing limited automotive volume and battery capacity. Based on the technological growth of electric machines and power electronics, the trend in the automotive industry is to replace conventional dc motor with BLDC motor based on electric motor technology.

This paper deals primarily with the design aspects of the drive for automotive applications such as water pump and VVA. Experimental results from a laboratory prototype are presented to validate the feasibility of the proposed BLDC drive.

Motor and controller for both water pump and VVA are located around the engine where the environmental temperature is about -40~125 [℃]. The motor and controller needs high reliability because the drive controls the engine system. In this paper, the devices, which has high operating temperature range, are selected. And also for the production, 8 bit processer was used.

II. MODELING OF BLDC MOTOR

A disadvantage in brush-type motors is their inherent brush and commutator requirement. The brushes tend to arc, which generates radio-frequency interference (RFI). The mechanical action of the brush sliding along the commutator can also create audible noise that may be objectionable in some applications. The brushes in some low cost DC motors may also need to be replaced in as little as 1000h of operation. The commutator and brush assembly can fail in a catastrophic manner under worst-case conditions, such as during a stalled or locked rotor. When electronic controls are added to a brush motor, it is sometimes worth upgrading to a brushless motor for increased performance.

A BLDC motor eliminates the brush and commutator assembly and operates indirectly from DC. Unlike the brush motor, whose armature resides on the rotor, the BLDC motor carries magnets. The BLDC motor is popular for many types of applications that cannot tolerate brushes and in equipment that requires good speed control plus high power efficiency [2].

The interior permanent magnet synchronous motor as the phase angle of the excitation current to properly control the reluctance torque without torque ripple could be used usefully. However, from the economic perspective, the reluctance torque of the brushless DC motor is not easy to use. In addition, it is difficult to adequately control magnet torque and reluctance torque, because magnet torque and reluctance torque cycle is different. In the case of a great reluctance torque, torque ripple in the motor is a cause of mechanical fatigue, noise and vibration. For these reasons, the surface mounted synchronous motor is used for the water pump and VVA.

Table I. is the specification of the BLDC motor for water pump. The BLDC motor has 6 poles and the maximum speed is 9,000 rpm, so that the inverter voltage fundamental frequency reaches 450 Hz. Table II is the specification of the BLDC motor for VVA. The BLDC motor has 10 poles and the maximum speed is 9,000 rpm, so that the inverter voltage fundamental frequency reaches 666 Hz.

TABLE I
SPECIFICATION OF THE BLDC MOTOR FOR WATER PUMP

Items	specification	Unit
Number of Poles	6	-
Number of Slots	9	-
Back EMF Constant	0.9	mV/rpm
Rated Torque	450	mNm
Input Voltage	9~18	V
Rated Speed	6,000	rpm
Maximum Speed at No Load	9,000	rpm
Operating Temperature	-40~125	℃

TABLE II
SPECIFICATION OF THE BLDC MOTOR FOR VVA

Items	specification	Unit
Number of Poles	10	-
Number of Slots	12	-
Back EMF Constant	1.1	mV/rpm
Rated Torque	350	mNm
Input Voltage	9~18	V
Rated Speed	6,000	rpm
Maximum Speed at No Load	8,000	rpm
Operating Temperature	-40~125	℃

The block diagram of BLDC motor drive is shown in Fig. 3.

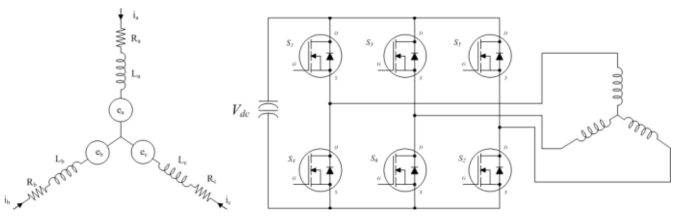


Fig. 3. Stator equivalent circuit and inverter configuration.

The coupled circuit equations of the stator winding in terms of motor electrical constants are

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where R is the stator resistance per phase, assumed to be equal for all three phases. The induced emfs e_a, e_b, e_c are all assumed to be trapezoidal.

If there is no change in the rotor reluctance with angle because of a nonsalient rotor, and assuming three symmetric phases, the following are obtained.

$$L_{aa} = L_{bb} = L_{cc}, L_{ab} = L_{ac} = L_{ba} = L_{ca} = L_{bc} = L_{cb} = M \tag{2}$$

Substituting equation (2) in equation (1) gives the BLDC motor model as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix}\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{3}$$

The stator phase currents are constrained to be balanced, which leads to the simplification of the inductance matrix in the model as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix}\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{4}$$

The electromagnetic torque is given by

$$T_e = [e_a i_a + e_b i_b + e_c i_c]\frac{1}{\omega} \tag{5}$$

Assuming that there is no phase difference between current and back-EMF, we can write the electromagnetic torque as

$$T_e = \frac{2EI}{\omega} \tag{6}$$

The interaction of T_e with the load torque determines how the motor speed is built up

$$T_e = T_L + J\frac{d\omega}{dt} + B\omega \tag{7}$$

Where, T_L is load torque, J is inertia, and B is the viscous damping [7].

III. OPERATION OF BLDC MOTOR

Consider the operation of the BLDC motor with six-switch inverter topology. Fig. 4 shows back-EMF and phase current waveforms, where the rotor is rotating in a counter clockwise direction at a speed of ω_m . This emf waveform has a flat portion, which occurs for at least 120 electrical degrees during each half-cycle. The amplitude E is proportional to the rotor speed. The back-EMF constant of water pump is 0.9 mV/rpm, and maximum operating speed is 9,000 rpm. Therefore, the amplitude E is 8.1 V at 9,000 rpm. And the back-EMF constant of VVA is 1.1 mV/rpm, and maximum operating speed is 8,000 rpm. Therefore, the amplitude E is 8.8 V at 8,000 rpm. This point is important to design the motor and drive. The operating minimum input voltage should be larger than back EMF at the maximum speed.

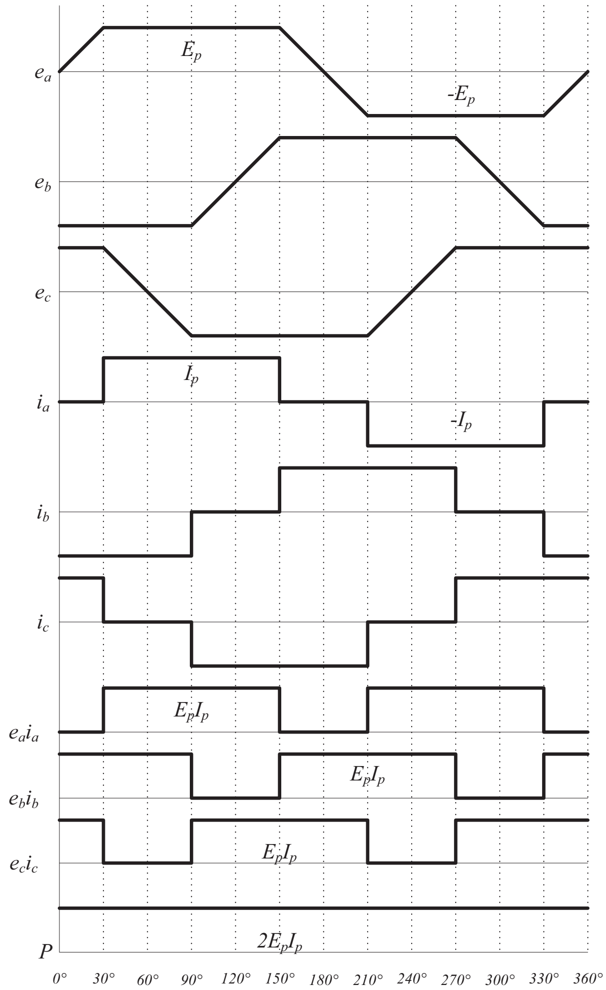
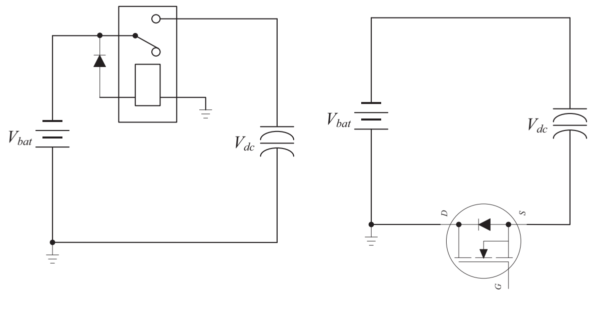


Fig. 4. BLDC motor waveforms.

IV. AUTOMOTIVE ELECTRICAL DESIGN CONSIDERATIONS

1. Reverse battery voltage protection

Most auto manufacturers specify that all electronic modules, such as motor controls, must be able to withstand reverse battery connections. The exact magnitude of the reverse voltage which can be tolerated varies with each auto manufacturer, but the extreme case appears to be -24V for 10min. The requirement to withstand reverse battery connections is especially troublesome with motor control



(a)Relay circuit (b)MOSFET circuit

Fig. 5. Reverse battery problems and protection method.

power designs, since they usually present a high current path when driven from a reversed power supply voltage. A simple reverse battery isolator relay can be used to guard against incorrect battery polarity connections [2]. But the relay is bulky and has a narrow range of operating temperature. It is important to reduce the size and to have a wide range of operating temperature in automotive applications.

To solve this problem, reverse voltage protection circuit with MOSFET composed. Fig. 5 shows a circuit and the flow at the reverse operation.

2. *Inrush current protection*

When the drive connects to the battery, current can rise sharply by charging the capacitor. Because of the high capacity of water pump drive, the inrush current is also very high. This occurs that the fuse of the vehicle can burn easily. To prevent high inrush current, the protection circuit is required.

The simple solution is the relay circuit. But the relay for high current is bulky and has a narrow range of operating temperature.

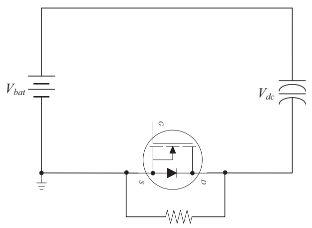
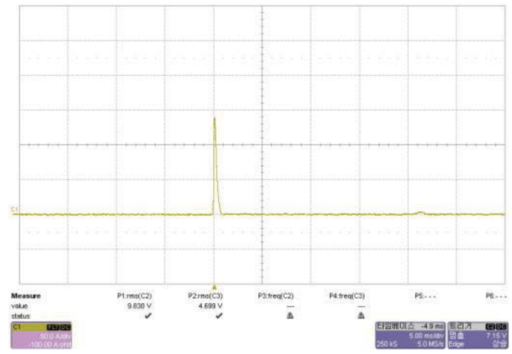


Fig. 6. Inrush current protection circuit.

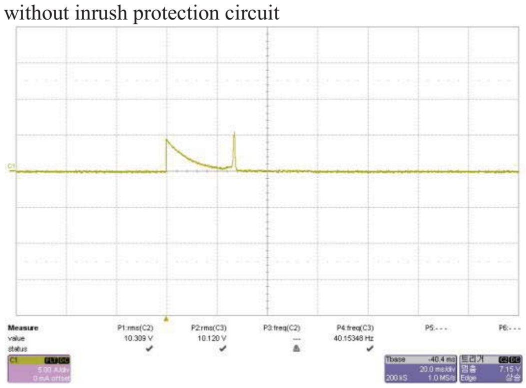
To solve this problem, inrush current protection circuit with MOSFET composed. Using a resistor, inrush current is controlled at the initial charge the capacitor. Fig. 6 shows a circuit to prevent high inrush current and Fig. 7 shows the current waveforms.

3. *High temperature consideration*

An electronic motor control must be rugged in order to withstand the stress levels encountered in the automotive environment, including temperature, humidity, vibration, jammed rotor, and long-term use [2]. The most severe condition of water pump is that ambient temperature is 120 [℃] and coolant temperature is 107 [℃]. And also the condition of VVA is around 125 [℃]. In this condition, the temperature of the control module rises to 150 [℃]. Because the controller is located around the engine. The parts of controller were selected by considering the environmental temperature. In order to prevent a lot of heat generation, heating elements is composed by separating each order. The top board consisted of passive components, and the bottom board consisted of the MOSFETs and control circuits to minimize signal pattern. Fig. 8 shows top board. By applying a bus-bar, the current loss is reduced. Fig. 9 shows the controller and the temperature of each component of high-temperature durability test.



(a) without inrush protection circuit



(b)with inrush protection circuit

Fig. 7. Current waveforms.

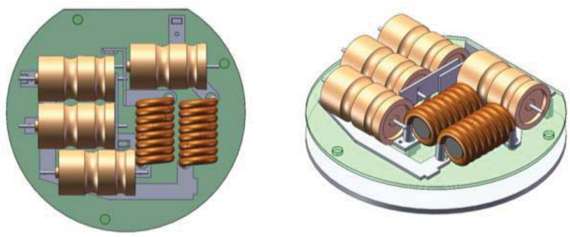


Fig. 8. Top board of controller.

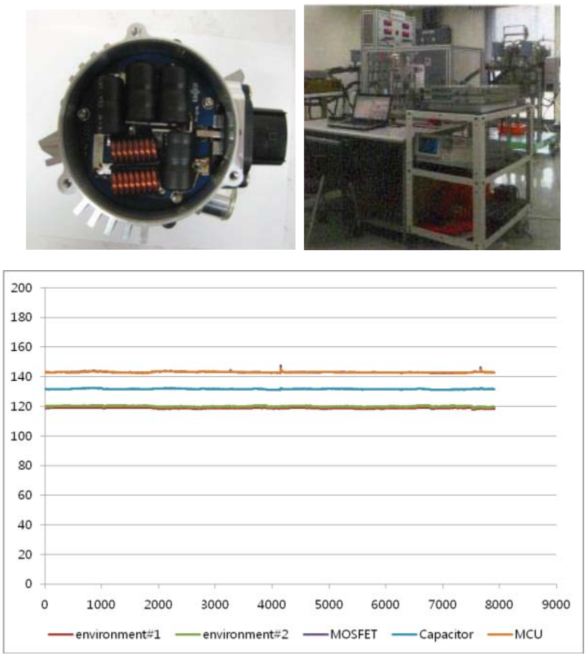
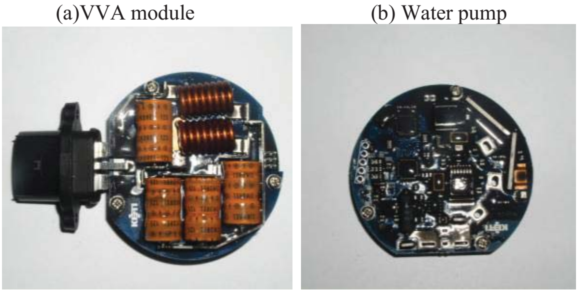


Fig. 9. High-temperature durability test

V. EXPERIMENTAL RESULTS

(a)VVA module (b) Water pump



(c)BLDC drive

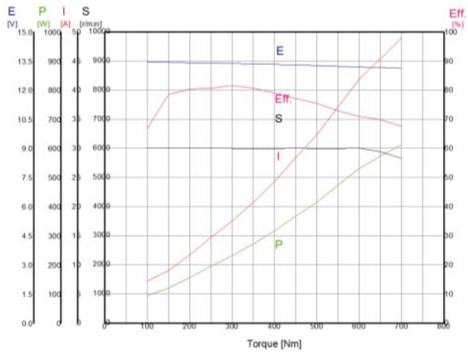
Fig. 10. Photos of VVA module, water pump and BLDC drive.

Fig. 10 shows photos of VVA module, water pump and BLDC drive. To apply the water pump and VVA, the drive was designed in the form of a round. The top board is passive component part and the bottom board is control circuit part. The size of a drive is 75X28 [mm] (diameter X height). The rated power is 350[W] and the rated power density is approximately 2.8 [kW/l].

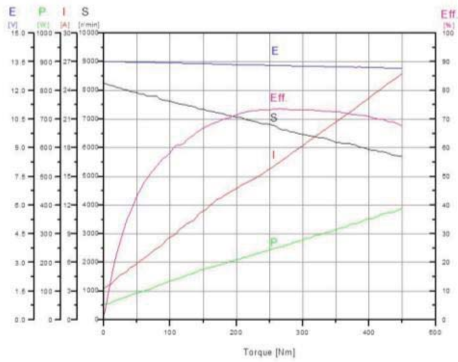
The BLDC drive was tested extensively with dynamometer load and evaluated its performance over various tests. Fig. 11 shows the experimental test setup. The desktop commands speed to the inverter by CAN communication. A power measuring device was installed at the input lines of the motor to measure the input power, current and voltage.

The specification of the motor drive is presented in table III. In consideration of production, 8 bit processor (XC886) was used. The Features of Speed-Torque-Current (N-T-I) in case of supplying 13.5V rated voltage are shown in Fig. 12. The satisfactory results for water pump are obtained the efficiency 77% at the point of rated torque, 450mNm. And the results for VVA are obtained the efficiency 73% at the point of rated torque, 350mNm.

Fig. 11. Photos of the experimental setup.



(a) Water pump motor



(b) VVA motor

Fig. 12. Measured performance curve of the BLDC motor and drive.

VI. CONCLUSION

This paper presents a design and implementation of BLDC motor drive for automotive applications. For the operation for automobile application, it is important to consider not only performance but also reliability. In order to enhance reliability, all parts of the drive, which the operating temperature range is over 150 degree, was chosen. And for the cost, the drive was simplified.

Through the experimental results, validity and quality of the reported designs are verified, and the motor and drive for water pump are obtained the efficiency 77% at the point of rated torque, 450mNm. And the motor and drive for water pump are obtained the efficiency 73% at the point of rated torque, 350mNm. The developed BLDC drive has been successfully applied to automotive applications.

TABLE III
SPECIFICATION OF THE MOTOR DRIVE

Items	specification	Unit
Nominal operating voltage	13.5	V
Operating voltage range	9~18	V
Operating current range	0~60	A
Size	75X28	mm
Processor	XC886	
Operating control	CAN communication	
Operation monitoring	Voltage, Current, Temperature, Speed	
Protection	Volatge, Current, Temperature, Reverse voltage, Speed	

REFERENCES

[1] T.J.E. Miller, and Hendershot, Design of Brushless Permanent-Magnet Motors, Magna Physics publishing and Clarendon Press, Oxford, 1994.

[2] Richard Valentine, Motor Control Electronics Handbook, McGrow-Hill Handbook, 1998.

[3] Grodon R. Slemon, "High-Efficiency Drives Using Permanent-Magnet Motors", *Proc. of IEEE IECON*, pp. 725-730, 1993.

[4] V. R. Stefanovic, "Opportunities in Motor Drive Research – A View from Industry", *Proc. of IEEE IECON*, pp. xxxvii-xxxxlv, 1995.

[5] M. A. Rahman, "Modern Electric Motors in Electronic World", *Proc. of IEEE IECON'93,* pp. 644-648, 1993.

[6] M. Zeraoulia, M. E. H. Benbouzid, and D.Diallo, "Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study", *Vehicular Technology, IEEE Trans. on*, vol. 55, Issue 6, pp. 1756-1764, 2006.

[7] R. Krishnan, Electric Motor Drives : Modeling, Analysis, and Control, Prentice Hall, 2001

[8] Palladino A., Fiengo G. De Cristofaro F., Casavola A., "In Cylinder Air Charge Prediction for VVA System : Experimental Validation", *Control Applications*, pp. 239-244, 2008.

[9] Yasuhiro Kue, Hideo Kobayashi, Hiroki Ichinose and Takayuki Otsuka, "Development of New Generation Hybrid System (THS II) – Development of Toyota Coolant Heat Storage System", *SAE International*, 2004-01-0643, 2004.