Development of BLDC Motor and Drive of VVA module for Automotive application

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Abstract- **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. To improve the fuel efficiency, it is necessary to reduce losses or to improve combustion efficiency of the engine. VVA (Variable Valve Actuation) 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 BLDC motor drives for VVA system.**

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 of engines, it is needed to improve the efficiency of the engine and reduce losses. VVA (Variable valve Actuation) 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 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].

In recent years, the brushless dc (BLDC) motor is attracting growing attention 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]. 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 permanent magnet brushless dc motor and Drive for VVA of automotive applications.

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

II. DESIGN OF A BLDC MOTOR

In the basic design, the basic shape and the motor specification are decided by magnetic load distribution method and characteristic analysis is performed by finite element method (FEM) and by equivalent magnetic circuit method (EMCM). Table 1 presents the designed parameters of the motor. Nd-bonded permanent magnets are adopted for a BLDC motor. Energy density of Nd-bonded material is superior to a ferrite which is mainly adopted BLDC motor. As can be seen in this figure, maximum flux density of stator yoke and rotor core is less than 1.5[T], which means each specific shape and size is designed well. The Fig. 1 (a) shows the Distribution of flux density and the (b) describes the features of Back EMF at 1,000rpm.

TABLE I
Specification of designed Motor

Items	Specification
Number of Poles	10
Number of phase	3
Number of Slots	12
Stack Length	45mm
Air-gap Length	0.5mm
Back EMF Constant	1.1 mV/rpm
Rated Torque	350 mNm
Rated Speed	6,000 rpm
Maximum Speed at No Load	8,000 rpm
Operating Temperature	-40~125 ℃

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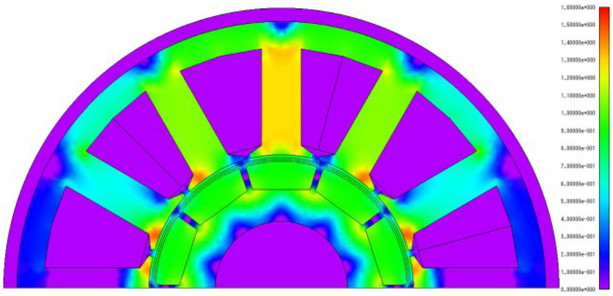
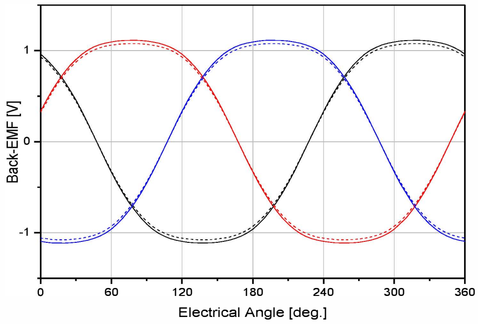


(a) Distribution of Flux density



(b) Characteristics of back EMF at 1,000rpm

Fig. 1. Distribution of Flux density and characteristics of back EMF at 1,000rpm

III. DESIGN OF A MOTOR DRIVE

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 [1],[2].

Fig. 2 shows the typical inverter configuration and current commutation sequence. Generally, a BLDC motor is wound in a three-phase wye configuration. This configuration connects one end of each phase together to make a center point of a "Y" or the motor neutral point. This is then driven by a three-phase inverter with what is called 120° commutation. At any step, only two of the three phases are conducting current where current flows into one phase and then out another. For instance, when phase A and B conduct current, phase C is floating.

A transition from one step to another step is called commutation. So, totally, there are six steps in one cycle. As shown in Fig. 2, the first step is AB (phase A and B conducting current), then to AC, to BC, to BA, to CA, to CB and then the pattern is repeated. In order to produce maximum torque, the inverter should be commutated every 60 electrical degrees so that current is in phase with the back EMF. The conducting interval for each phase is 120 electrical degrees, or two steps.

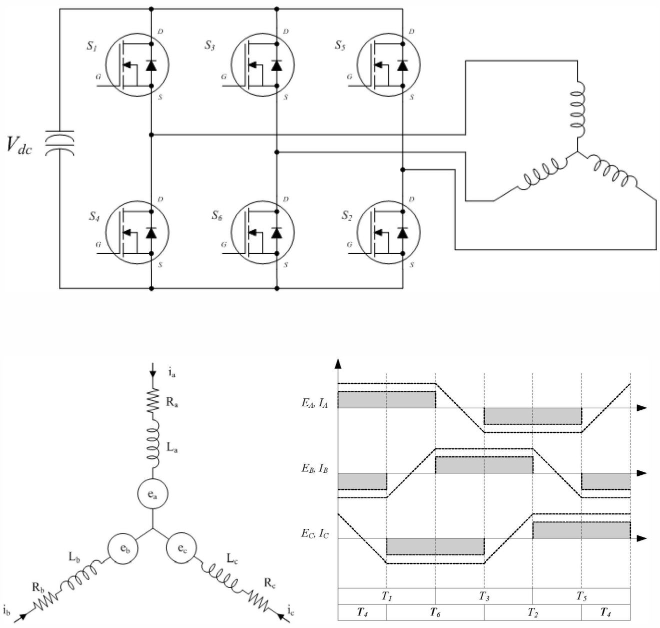


Fig. 2. Inverter configuration and current commutation sequence for BLDC

A. *Hall sensor balancing*

In the case of sensor-less control, the commutation timing is determined every 60 electrical degrees by detecting when the back EMF on the floating phase crosses the zero crossing point (ZCP). The ZCP of the back EMF can be obtained by comparing the terminal voltage to the neutral point [3]. The sensor-less control has been offered to eliminate the costly and fragile position sensor. Typically, practical minimum speed of the conventional sensor-less drive is around 10% of the rated speed [4]. The sensor-less control is suitable for a wide range of applications where closed-loop operation near zero speed is not required. However, the BLDC motor for VVA module is required for wide speed range of motor and for forward and reverse operation. To accomplish these, sensored control is applied for VVA module. This sensored control is mainly under assumption that the hall sensors are ideally placed 120 degrees apart. However, this assumption is not always valid. Sensor placement may be significantly inaccurate [5].

Recently, various hall sensor balancing controls have been developed as an measure of rotor position, which are categorized as methods based on filtering [5], [6], and vector tracking observer [7]. However, for these technologies, high performance processor is needed.

For balancing hall sensors, the ZCP of the back EMF can be obtained by comparing the terminal voltage to the neutral point at low speed. And then, ZCP is compared to hall sensor signal. This error is applied control algorithm. After hall sensor alignment, the target speed is reached.

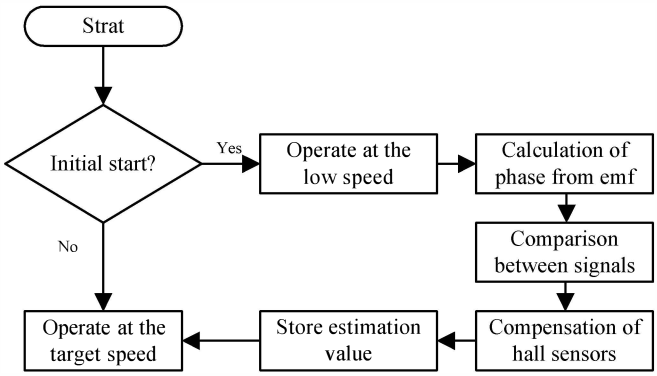


Fig. 3. Flowchart of position estimation.

Fig. 3 shows a flowchart of BLDC control for VVA module. At first time of starting the BLDC motor for VVA module, it operates square-wave current motor with signal of hall sensors. This method is the way to control BLDC motor mostly. By comparing the hall sensor and back-emf signal, the phase difference between two signals is calculated. In order to reduce errors, it operates during the position estimation at a low speed. And it is difficult to find precise zero-crossing point of back-emf without additional circuit and high resolution processor. However a method that the angle is inferred from the back-emf is simple and does not need additional circuit. This estimation process is required only once and can be achieved in the production process.

B. *Protection of motor drive*

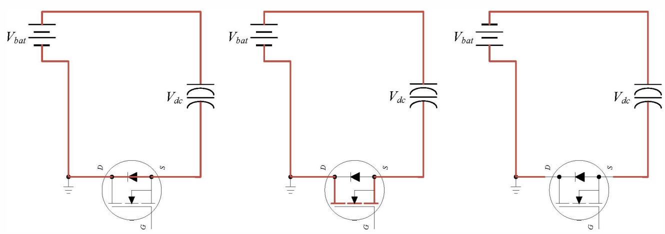


Fig. 4. Flow at the forward and reverse operation.

In the case of reverse dc-link voltage, it badly damages the drive. To protect the drive, it is essential to apply protection circuit. A relay is widely used for protection of reverse dc-link voltage in the electrical drives. 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. It is more important because VVA locates around the engine.

To solve this problem, reverse voltage protection circuit with MOSFET composed. Fig. 4 shows a circuit and the flow at the forward operation. At initial power-on, the drive operates through the body diode and then the MOSFET is turned on by applying a gate signal.

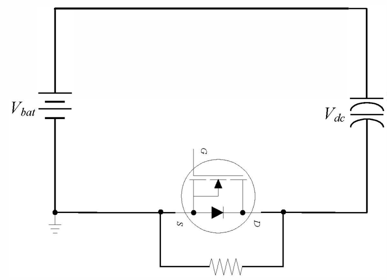


Fig. 5. Inrush current protection circuit.

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.

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. 5 shows a circuit to prevent high inrush current.

IV. Experimental Results

Fig. 6 shows photos of the BLDC drive. To apply VVA module, the drive was designed. The top board is control part and the bottom board is power circuit part for cooling. The size of a drive is 70X110[mm]. The rated power is 250[W].

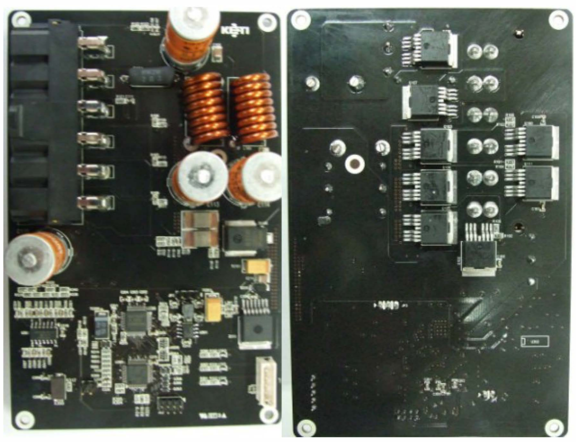


Fig. 6. Photos of the BLDC motor drive.

The BLDC drive was tested extensively with dynamometer load and evaluated its performance over various tests. Fig. 7 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 Features of Speed-Torque-Current (N-T-I) in case of supplying 13.5V rated voltage are shown in Fig. 8. The satisfactory results are obtained the efficiency 72% at the point of rated torque, 350mNm.

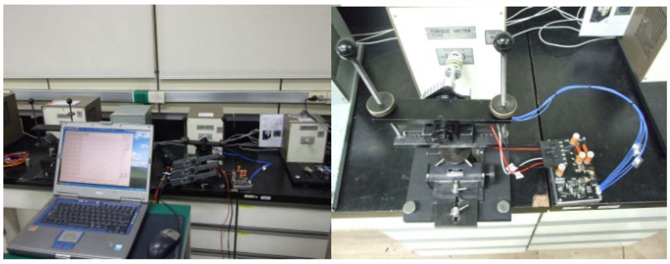


Fig. 7. Experimental setup.

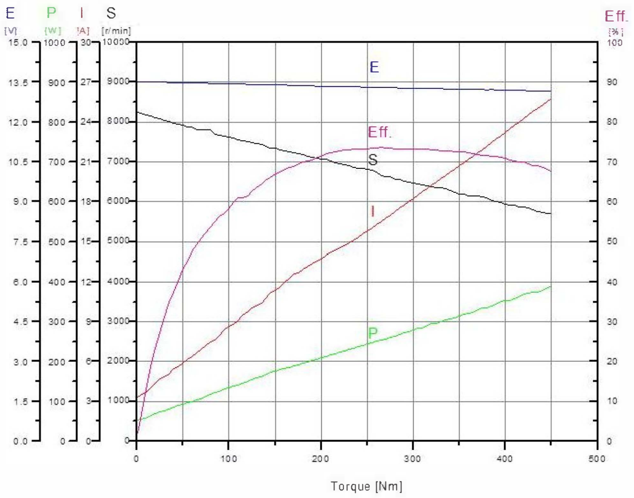


Fig. 8. NTI curve.

V. CONCLUSION

This paper deals primarily with the design aspects of the permanent magnet brushless dc motor and Drive for VVA of automotive applications. The device, which has high operating temperature range, is selected. And also for the production, 8 bit processer was used.

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