BLDC Drive Control of Electric Water Pump for Automotive Application

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***Abstract*-This paper presents the BLDC drive design of water pump system for automotive application. Electric water pumps offer several advantages. Among them, the efficiency is the main reason for electric water pumps. 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. The way which the mechanical water pump is replaced by electric water pump could reduce energy consumption. Besides, electric vehicle (EV) do not have the internal combustion engine. Therefore, the EV needs a electric water pump for cooling traction motor and inverter. The electric water pump concept is not new and already introduced [3, 4]. However, the papers mainly introduced overall pump system. This paper deals primarily with the design aspects of the BLDC drive for the water pump. The drive requires sustain temperatures of over 110 [℃]. Rated power is 350 [W] and input voltage is 13.5 [V].**

Keywords : Electric Water Pump, Inverter, BLDC Control, PWM

I. INTRODUCTION

Environmental and economical prospects give a fresh impetus to develop clean, efficient, and sustainable vehicles for urban transportation. Vehicle is the most popular means of transportation. However the internal combustion engine (ICE) vehicles provide the major source of urban pollution that causes global warming. The number of automobiles on our planet doubled to about a billion or so in the last 10 years [1]. Due to these the environmental issues, automobile technology continue to make significant progress in all of these areas and through innovations in gasoline engine fuel conversion efficiency, cleaner and quieter diesel engines and increased use of alternative fuels [2]. Under these circumstances, the mechanical parts in the automobile industry are being replaced by electronic methods. 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. 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.

However, key issues are cost and reliability of the electrical equipment for the automobile applications. Challenges include the harsh automotive environment where temperatures can reach as high as 150 [℃] under the hood. However, cost remains the overriding challenge facing the developers of automotive electrical accessory equipment [3]. The concept of automotive water pump is already introduced [3, 4]. The papers mainly reported overall concept of water pump system for automotive applications. And also the design of motor for the automotive accessory is introduced well [5, 6]. Edward C. Lovelace et al [5] reported impact of saturation and inverter cost based on interior PM synchronous machine drive optimization. And Surong Huang et al [6] reported an approach to sizing and power density equations.

The key objective of this paper is to describe how the inverter drive system for the water pump is designed. The physical layout is an integrated system as introduced the papers [3, 4]. BLDC motor is applied.

II. MOTOR AND CONTROLLER SPECIFICATIONS

A specifications of motor and controller are presented in following Table I. The nominal 13.5 [V] operating voltage was chosen to apply not only EV but also current automotive systems. The rated power of the motor is 350 [W]. And the temperature of the coolant can rise as high as 110 [℃]. Therefore, the drive requires high current device for PWM switching. 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 I
SPECIFICATION OF MOTOR AND CONTROLLER

Items	Specifications
Number of Poles	6
Number of Slots	9

Rated Torque	450 [mNm]
No Load Speed	8,500 [rpm]
Rated Speed	6,000 [rpm]
Input Voltage	9~18 [V]
Rated Voltage	13.5 [V]
Rated Efficiency	78 [%]
Operating Temperature	-40~125 [℃]

III. DESIGN OF BLDC MOTOR DRIVE

A. *Device Selection Considering Operating Temperature*

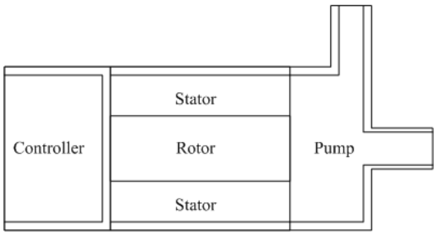


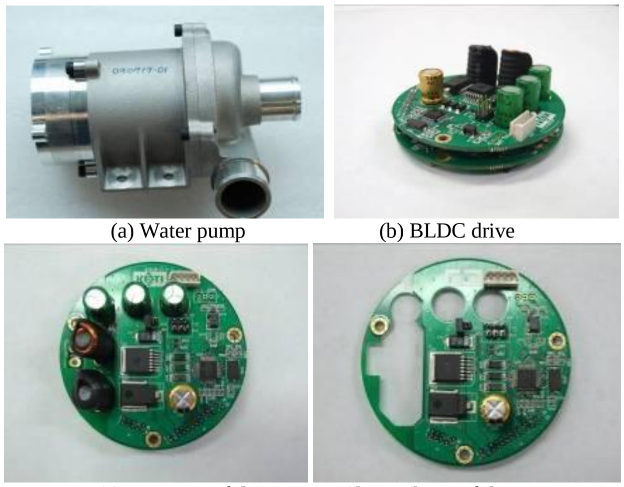
Fig. 1. prototype sketch of integrated water pump

Before developing the water pump drive, it is necessary to consider operating temperature. The motor controller is directly connected to the BLDC motor and the capacity is 350 [W]. The water pump is located near the engine room. Therefore ambient temperature of the water pump is similar to the engine room. In the worst case, coolant temperature could reach 110 [℃]. Considering the coolant temperature, the high temperature devices for the water pump should be selected. Figure 1 shows prototype sketch of integrated water pump. Switching device is located between motor and controller for cooling. Assuming 110 [℃] coolant temperature, the temperature of the switching device reach at 150 [℃]. Therefore, it is essential to select the switching device which is operated at 150 [℃]. The maximum current of the controller is 60 [A] and the operating voltage is 9~18 [V]. Considering these points, the Infineon IPB180N series was chosen as MOSFET.

It is also important to select electrolytic capacitor. In the inverter, the capacitor is continuously charging and discharging. Therefore, the operating temperature of the capacitor is also high. Lots of companies produce capacitor having high operating temperature. However, most of electrolytic capacitors having 150 [℃] operating temperature are too bulky to apply the prototype water pump drive. Therefore, VA series of Samhwa Electric was selected as DC link capacitor. This capacitor has The load life of 4000 hours at 130 [℃].

All devices for water pump drive except micro controller and electrolytic capacitor was chosen that the operating temperature is at least 125 [℃].

B. *Size Issue for Water Pump Drive*



(a) Water pump (b) BLDC drive

(c) Top view of drive (d) Top layer of drive

Fig. 2. Photos of water pump and BLDC drive

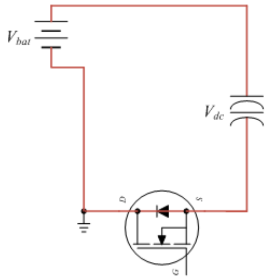
The water pump is located near the engine room. The space of engine room is not enough. In order to apply to the automotive water pump, it is necessary to integrate and miniaturize pump, motor and controller. It is important to place the components of controller. The space of controller is 75x32[mm](diameter x height).

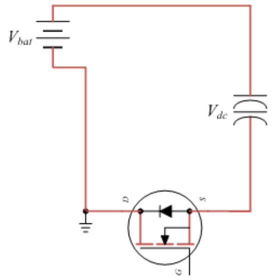
To apply the water pump, the drive was designed in the form of a round. The controller consists of two boards which are control board and power board. The top board is control part and the bottom board is power circuit part. For cooling, MOSFET is placed on the bottom of the power board. Through the proper placement of the components and optimal design, the size of entire controller is 75x28[mm]. The rated power is 350 [W] and the rated power density is approximately 2.8 [kW/l].

C. *Protection of Reverse Voltage*

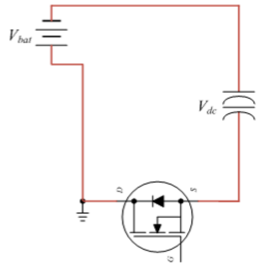
Automotive application is DC voltage system. The DC voltage system always must be careful of reverse voltage. In the case of reverse dc-link voltage, it badly damages the controller. To protect the controller, it is essential to apply protection circuit. A relay is widely used for protection of reverse 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 the water pump locates around the engine room.

To solve this problem, reverse voltage protection circuit with MOSFET composed. Fig. 3 (a), (b) 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. 3 (c) shows a circuit at the reverse operation. At initial power-on, the diode of MOSFET is reverse and the MOSFET is not turned on. Therefore, the controller is protected from reverse voltage.





(a)Flow at initial power-on (b) Flow after initial power-on



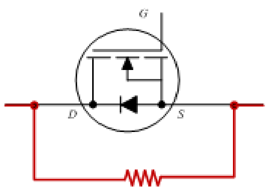
(c) Flow at reverse operation

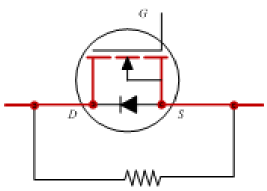
Fig. 3. Flow at the Forward and Reverse Operation

D. Limitation of Inrush Current

The inrush current is the waveform of the input current, measured immediately after the input voltage is connected. When the power switch to the supply is initially turned on, the bulk capacitor initially appears effectively as a short circuit, which may result in an unacceptably large inrush current [7]. To limit this inrush current, a thermister, which initially has a large resistance when it is cold, is widely used. However, the water pump system has wide range of operating temperature, and therefore it is not suitable to apply the thermister. And a relay to switch, which is widely used, is not suitable for the water pump. The relay is bulky and has a narrow range of operating temperature.

By considering terms of size and operating temperature, a MOSFET is applied as a switch. Fig 4 shows flow at the initial turned-on. Initially the MOSFET is off and the current limiting resister limits the inrush current at turn-on. When the bulky capacitor voltage charges up, the MOSFET is turned on, thus bypassing the current limiting resistor.

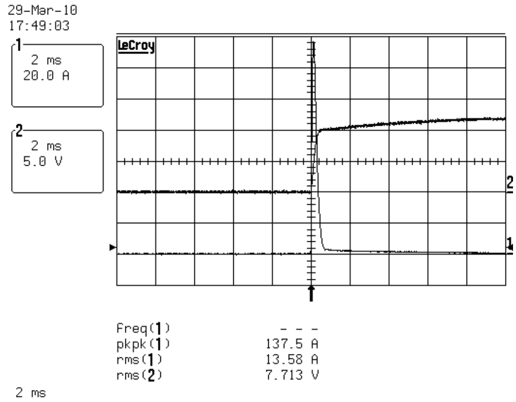




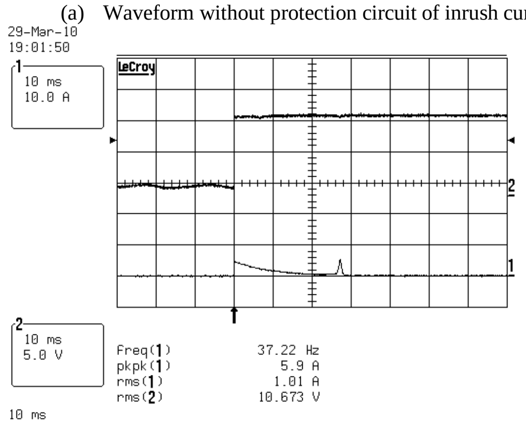
(a) At initial turned-on (b) after charging the bulky capacitor

Fig. 4. Flow at the initial turned-on

Fig 5 shows experimental results with protection circuit for inrush current and without the circuit. The switching timing is determined by a combination of resistor and capacitor connected to the gate of MOSFET. The peak value of the inrush current without protection circuit is reached at 137 [A]. however, the peak current with protection circuit is limited at 5 [A].



(a) Waveform without protection circuit of inrush current



(b) Waveform with protection circuit of inrush current

Fig. 5. Voltage and Current Waveforms with and without Protection Circuit

E. Operation of BLDC Motor

The block diagram of BLDC motor drive is shown in Fig. 6. e_{as}, e_{bs}, and e_{cs} are trapezoidal shaped back-EMFs, and R_s is a shunt resistor for current sensing, and Z_m=L_s+R.

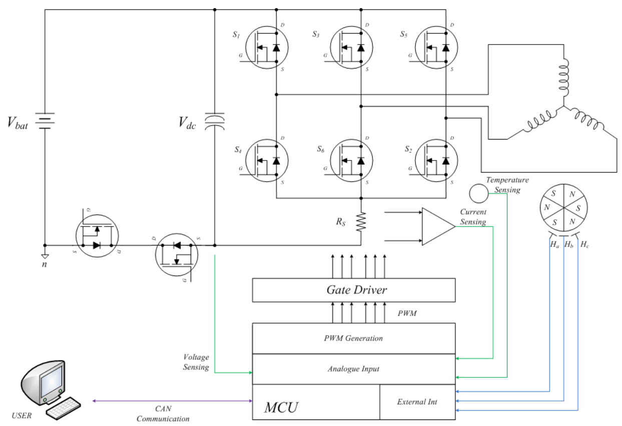


Fig. 6. Block Diagram of BLDC Motor Drive

The BLDC motor can be represented as

$$
\begin{aligned}
v &= Ri + \frac{d}{dt}\left[L_s(\theta_r)i + \lambda_M\right] \\
&= Ri + L_s(\theta_r)\frac{di}{dt} + i\omega_r \frac{d}{d\theta_r} L_s(\theta_r) + e
\end{aligned} \tag{1}
$$

However, the term of $i\omega_r dL(\theta_r)/d\theta_r$ is zero because there is no change in inductance according to the position. Therefore, the motor can be represented as

$$
v = Ri + L_s \frac{d}{dt} i + e
$$

$$
\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \tag{2}
$$

where i_a, i_b and i_c are phase current, and V_a, V_b and V_c are phase voltage.

The electromagnetic torque is expressed as

$$
T_e = \frac{1}{\omega_r}(e_{as}i_a + e_{bs}i_b + e_{cs}i_c) \tag{3}
$$

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

$$
T_e = \frac{2EI}{\omega_r} \tag{4}
$$

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

$$
T_e = T_L + J\frac{d\omega_r}{dt} + B\omega_r \tag{5}
$$

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

Some applications in automotive field require low torque ripple, e. g. electric power assisted steering. To achieve this, a sinusoidal current control could be a solution. The requirement of a low torque ripple is not main priority for small power water pump. Therefore, the squire-wave current control is preferred over the more expensive sinusoidal current control [4].

Consider the operation of the BLDC motor with six-switch inverter topology [8, 9, 10]. Fig. 7 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 degree during each half-cycle. The amplitude E is proportional to the rotor speed. The back-EMF constant 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. 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.

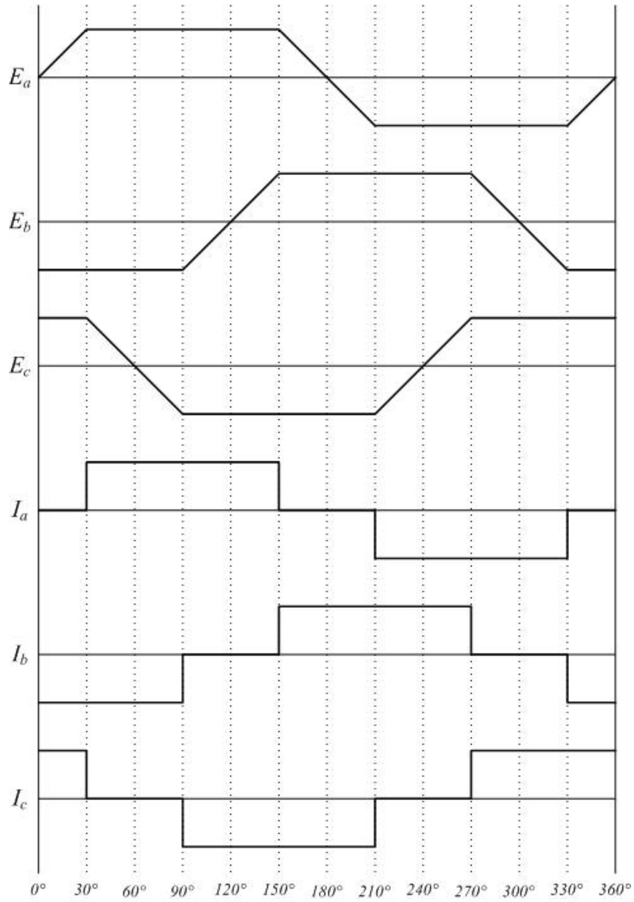


Fig. 7. Back-EMF and Phase Current Waveforms

The proportional-integral (PI) control scheme has been widely used for the speed control of motor drives. In this application, PI control scheme is used as the speed controller. The mechanical angular frequency is calculated from hall sensor signal. Fig. 8 shows overall block diagram for the Controller. In the block diagram, parameters with superscript * denote command value and K_b is back EMF constant.

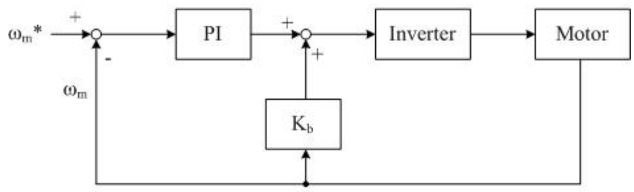


Fig. 8. Block Diagram of Controller

IV. EXPERIMENTAL RESULTS

Fig. 9 shows photos of the BLDC drive and experimental setup. To apply the water pump, the drive was designed in the form of a round. The top board is control part and the bottom board is power 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 were tested extensively with dynamometer load and evaluated its performance over various tests. Fig. 9 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.

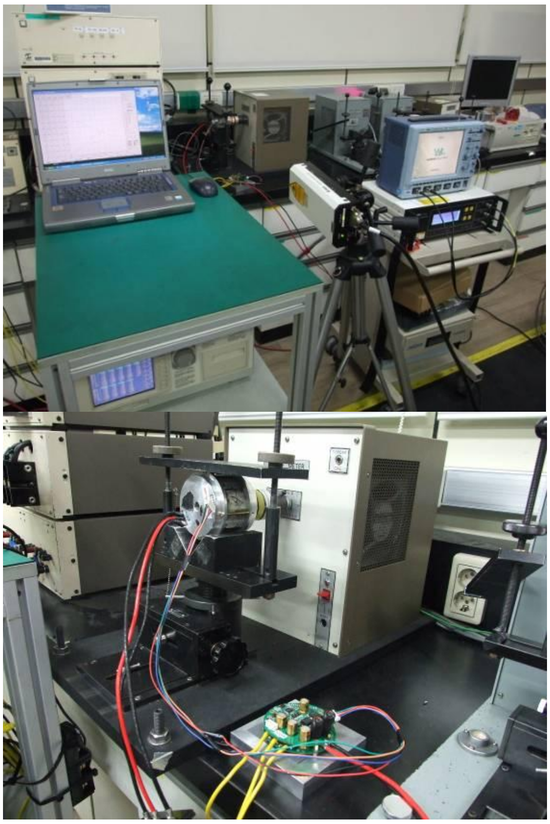


Fig. 9. Photos of the Experimental Setup

In consideration of production, 8 bit processor (MC9S08DZ32) was used. The Features of Speed-Torque-Current (N-T-I) in case of supplying 13.5V rated voltage are shown in Fig. 10. The satisfactory results are obtained the efficiency 78% at the point of rated torque, 450mNm.

V. CONCLUSION

This paper presents a design and implementation of BLDC motor drive for the automotive water pump. For the operation of a water pump for automobile application, it is important to consider not only performance but also reliability. In order to enhance reliability, all parts of the controller, which the operating temperature range is over 125 [℃], 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 are obtained the efficiency 78% at the point of the rated torque, 450 [mNm]. The developed BLDC drive has been successfully applied to the automotive water pump.

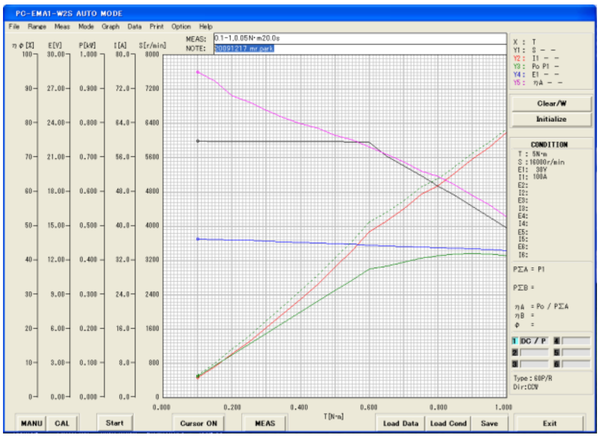


Fig. 10. Measured Performance Curve of the BLDC Motor and Drive

REFERENCES

[1] Iqbal Husain, *Electric and Hybrid Vehicles,* CRC Press, 2003.

[2] John M. Miller, *Propulsion Systems for Hybrid Vehicles,* IEE Power & Energy Series 4, 2004.

[3] Nathan C. Harris, Thomas M. Jahns, and Surong Huang, "Design of an Integrated Motor/Controller Drive for an Automotive Water Pump Application," Industry Applications Conference, 2002, pp.2028-2035.

[4] H. Hembach, S.A. Evans, and D. Gerling, "Systematic Comparison of BLDC Motors for Small Automotive Water Pump Applications," ICEM, 2008, pp.1-5.

[5] Edward C. Lovelace, Thomas M. Jahns, and Jeffrey H. Lang, "Impact of Saturation and Inverter Cost on Interior PM Synchronous Machine Drive Optimization," *IEEE Trans. Ind. Applicat.*, vol. 36, Issue 3, pp. 723-729, 2000.

[6] Surong Huang, Jian Luo, Franco Leonardi, and Thomas A. Lipo, "A General Approach to Sizing and Power Density Equations for Comparison of Electrical Machines," *IEEE Trans. Ind. Applicat.*, vol. 34, Issue 1, pp. 92-97, 1998.

[7] Ned Mohan, Tore M. Undeland, and William P. Robbins, *Power Electronics*, John Willey & Sons, 1995.

[8] Richard Valentine, *Motor Control Electronics Handbook*, McGrow-Hill Handbooks, 1998.

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

[10] R. Krishnan, *Electric Motor Drives*, Prentice Hall, Inc. 2001.

[11] Yasuhiro Kuze, Hideo Kobayashi, Hiroki Ichinose, and Takayuki Otsuka, "Development of New Generation Hybrid System(THS-II)-Development of Toyota Coolant Heat Storage System," SAE technical paper series, 2004.