Dry run detection method of sensorless brushless motor in motor speed feedback control system

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ABSTRACT: Because of the voltage FF (Feedforward) control specification of conventional electric liquid pumps, when the motor is driven with no liquid at all in the pump chamber, the motor speed will be very high compared to the speed when the pump chamber is filled with liquid. If the pump continues to be driven in this condition, the components of the pump may wear out or, in extreme cases, break. To address this issue, when the motor speed exceeds a certain value, a dry run is detected and a fail operation is performed to prevent damage to the pump. However, in vehicle systems that require motor speed FB (Feedback) control for the pump, a backlash has been found that prevents detection of dry running in the same way. Therefore, in this study, we established a method to detect dry running of pumps that require FB control without additional hardware such as sensors.

KEY WORDS: electric vehicle, brushless DC motor, dry run

1. INTRODUCTION

In recent world trend, environment restriction is more severe in The Safer Affordable Fuel Efficient (SAFE) Vehicles Proposed Rule and European emission standards. Therefore each vehicle company has tried to reduce CO2 emission, improve fuel efficiency by idle stop, design and develop HV vehicle with more efficient battery to achieve restriction. But engine is stopped during idle stop, therefore mechanical pump connected to engine is stopped too. By this phenomena, clutch oil pressure is not maintained and vehicle restart shock is large and driver feels uncomfortable. Moreover, inverter temperature is needed to adjust to improve efficiency of HV vehicle. Engine is stopped, therefore mechanical pump is stopped too and inverter temperature rises and efficiency becomes worse. To improve the fact above, demand of Electric Oil Pump to maintain oil pressure during engine stop and Electric Water Pump to cool down inverter during engine stop is expanding all over the world.

In the small motor available on Electric Oil Pump and Electric Water Pump, sensorless brushless motor with driver which schematics is listed Figure.1 is used instead of conventional DC motor. Electric pumps can be in a state where there is no liquid at all in the pump chamber due to broken piping or poor connection between the pump and piping.

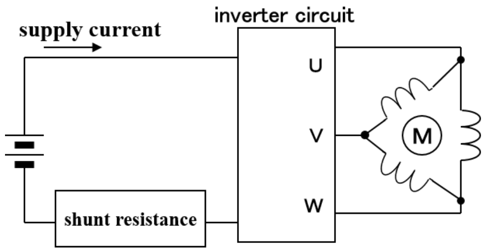

Fig. 1 Example of driver circuit

Even if the motor is driven in such a condition, it is difficult to ensure hydraulic pressure and inverter cooling satisfactorily because no liquid exists in the pump piping. In addition, an electric pump with voltage FF control may have a very high rotational speed, which is much higher than the speed when the pump chamber is filled with liquid, which may cause wear and tear of the pump components or, in extreme cases, damage to the pump. Various methods have been proposed for detecting whether a motor is dry running or not. One method is to detect dry running and perform a fail operation when the motor speed exceeds a certain value. [(1)] However, in vehicle systems that require motor speed FB control for the pump, a backlash has been found that prevents detection of dry running in the same way.

Therefore, in this study, we established a method to detect dry running of pumps that require FB control without additional hardware such as sensors.

2. Comparison of dry run detection methods

2.1. Problem with conventional methods of detecting dry running

Conventional dry run detection methods have been established to detect when the motor speed exceeds a certain value [1] or when the power supply current flowing in the driver current circuit shown in Figure 1 falls below a certain value. [2] Electric liquid pumps have load characteristics that can be approximated by a quadratic function, and the power supply current decreases rapidly as the rotation speed decreases. As shown in Figure 2, the power supply current increases or decreases according to the power supply voltage applied to the pump and the ambient temperature, so it is common practice to determine the detection threshold by considering the variation of the power supply current. However, as shown in Figure 3, when the rotation speed is low (4000 rpm or less), the difference between the power supply current during idling and normal operation is small, and the issue remains that dry running cannot be accurately detected.

To solve this problem, we propose a logic that can accurately detect idling even in a rotation speed FB system by software modification without hardware modification such as the addition of a new sensor. Table 1 shows the motor specifications used in this study, and Table 2 shows the evaluation conditions.

Table 1 Specification of brushless DC motor

Number of slots	6
Number of poles	9
Typical voltage	13.5 [V]
Typical output	60 [W]
Rated motor speed	6000 [rpm] @ 13.5 [V]

Table 2 Evaluation environmental conditions

Supply voltage	10.5 – 16.0 [V]
Ambient temperature	-40 – 105 [degC]
Pump load	w/ load, w/o load(dry run)
Drive system	Vector control
I_{dref}	0 [A]

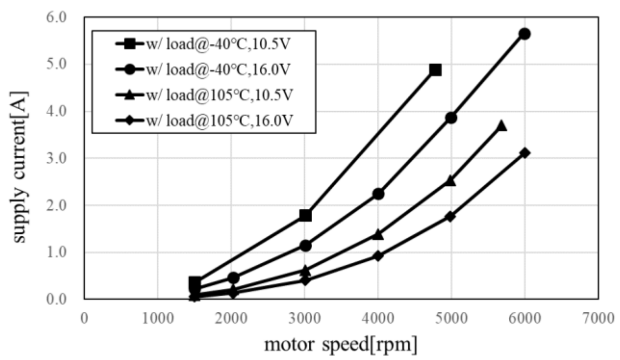

Fig. 2 Supply current value at rated load drive

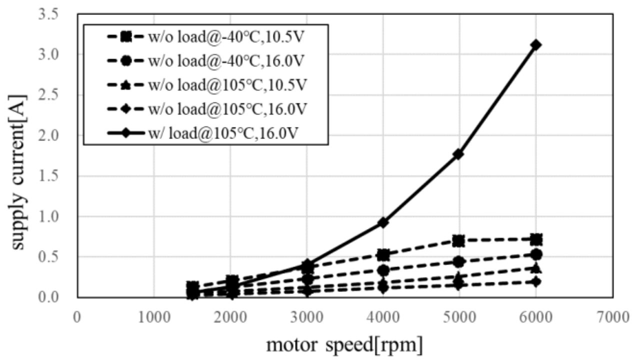

Fig. 3 Comparison results of power supply current during dry run and normal operation

2.2. Dry running detection logic using q-axis current

This system detects whether the motor is dry running or not using the q-axis current obtained by 3-phase-2-phase conversion of the UVW phase current detected from the shunt resistor shown in Figure 1 and the motor speed estimated from the detection of rotation speed block. The control block diagram employed in this study is shown in Figure 4. The liquid pump is constructed to control the motor speed according to the speed instruction ω_{ref} received from the vehicle ECU, and the d- and q-axis currents I_d, I_q are calculated by converting the phase currents $I_U, I_V,$ and I_W that flow when the motor is driven. An inverter circuit is used to drive the motor, and the U, V, and W phase voltages $V_U, V_V,$ and V_W applied to the inverter circuit can be obtained by converting the d- and q-axis voltage indication values V_{dref}, V_{qref} to 3- and 2-phase. The d- and q-axis voltage indication values V_{dref}, V_{qref} are calculated by comparing the feed backed I_d, I_q with the d- and q-axis current indications I_{dref}, I_{qref} required to converge to the motor speed instruction value ω_{ref}. In this study, the d-axis currents are set with the d-axis current command value $I_{dref} = 0$[A].

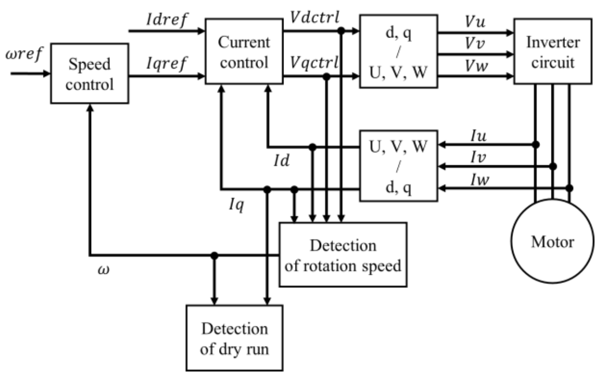

Fig. 4 Block diagram of dry run detection control

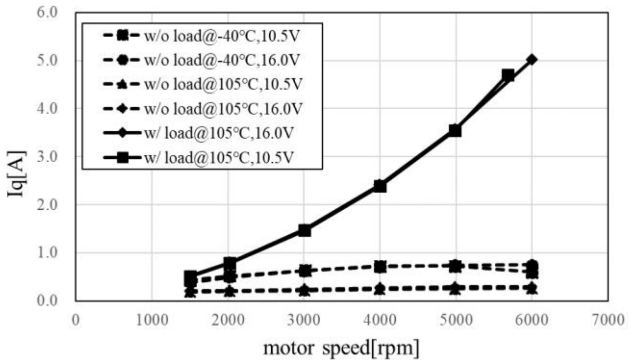

Fig. 5 Result of q-axis current comparison between dry running and normal operation

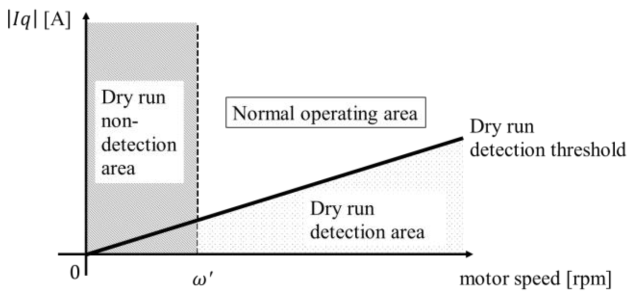

Fig. 6 Conceptual diagram of dry run detection

The motor speed ω is calculated from the d- and q-axis currents I_d, I_q and the d- and q-axis voltage indication values V_{dref}, V_{qref} obtained in the calculation process.

The dry run detection logic proposed in this study compares the q-axis current I_q with the dry run detection threshold calculated from the motor speed ω, and detects when the q-axis current I_q falls below the calculated threshold. The q-axis current characteristics when driven by this system are shown in Figure 5. The q-axis current fluctuates less with respect to the power supply voltage applied to the pump and the environmental temperature than the fluctuation range of the power supply current shown in Figure 2, so it can stably detect dry running in systems such as automobiles, where the power supply voltage fluctuates. The determination threshold for detecting dry running can also be simplified. However, since it is difficult to judge dry running in all motor speed ranges even if it is judged by the q-axis current, according to the graph shown in Fig. 6, dry running judgment is performed when the motor is driven at a speed ω' above a certain value.

2.3. Results of dry run detection using q-axis current

The proposed dry run detection logic was verified using a motor with the specifications shown in Table 1. In the evaluation environment shown in Table 2, the proposed method was employed against the conventional method. As a result, we succeeded in expanding the speed range in which dry running can be detected, and dry running can be detected at 3000 rpm or higher. In addition, since it is no longer necessary to consider the effect of power supply voltage fluctuation, the derivation of the dry run detection threshold has been simplified, leading to a reduction in development man-hours.

3. CONCLUSION

As described above, by changing the dry run detection logic for sensorless brushless motors in the speed FB control system from the conventional power supply current to q-axis current, we have succeeded in expanding the range in which dry run can be detected. Quantitative comparisons showed that the conventional logic for detecting motor idleness using the power supply current could only detect dry running at 4000 rpm or higher, but with this system, dry running can be detected at 3000 rpm or higher. This is an improvement of 16.6% (1000 rpm/6000 rpm ≈ 0.16) over the rated speed of 6000 rpm. In addition, since it is no longer necessary to consider the effects of power supply voltage fluctuations, the derivation of the dry run detection threshold has been successfully simplified, leading to a reduction in development man-hours, and this technology can be implemented at low cost through software modifications without the need for additional hardware such as sensors.

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