Development of Sensorless Motor Current Control with Reduced Size and Weight

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Feedback control and failure detection for an electric control unit equipped with a brushless motor is now achieved with three independent, phase-related current sensors. However, these sensors obstruct the downsizing of the electric control unit. Therefore, we developed a new open-loop current control strategy by using a single current sensor achieving the equivalent control accuracy and failure detection capability. This control strategy enables the downsizing and weight reduction of electric control units.

***Key Words**: brushless motor, single current sensor, motor current control, downsizing and weight reduction*

1. Introduction

JTEKT's flagship product, electric power steering (EPS), is highly regarded for being more energy-saving and environmentally-friendly compared with hydraulic power steering[1-3]. **Figure 1** shows a column type EPS system. An EPS system works by generating assist torque in the motor in response to the driver's torque on the steering wheel, then creating the necessary rack axial force to change road wheel direction. The motors used for power assist with brushes causing significant frictional loss have been replaced by three-phase brushless motors advantageous for increasing higher output. In order to apply brushless motors to EPS, the accuracy of motor torque, which effects steering feeling, is demanded, therefore, electrical current feedback control, as shown in **Fig. 2 (a)**, is used, whereby electrical current sensors are located on each phase. However, the usage of electrical current sensors is associated with electrical power loss, which results in reduced motor output. Therefore, in order to improve the downsizing and weight reduction features of the brushless motor, a new control system without electrical current sensors as shown in **Fig. 2 (b)** has been considered. In this system, motor torque control of good accuracy is our technical issue. This paper reports on a newly developed motor current control technology.

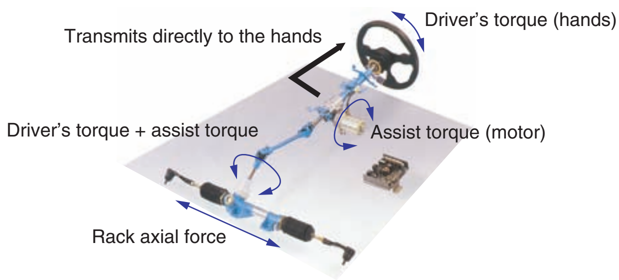

Fig. 1 EPS system (column type)

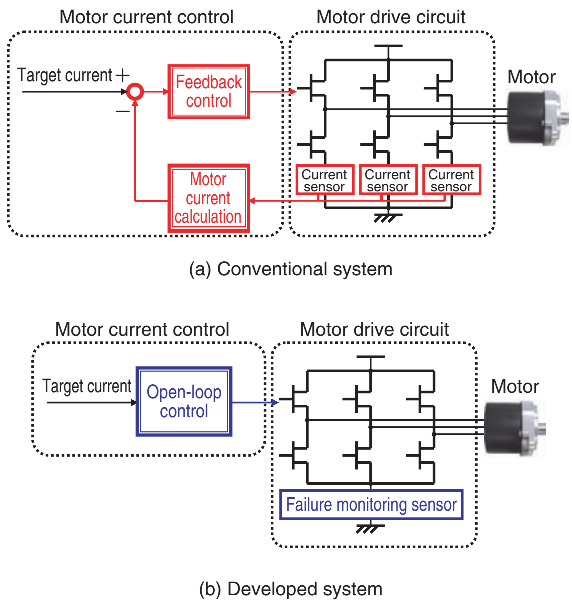

Fig. 2 Motor current control and drive circuit

2. Control Method

In order to remove the electrical current detection circuit, rather than the commonly used electrical current feedback control, open-loop control with a predetermined target current to the motor is necessary. However, open-loop control was not considered appropriate for use in EPS systems due to the inability to output highly accurate motor torque depending on the target current. This development makes control with accurate motor torque possible through the development of "variation compensation technology" and "torque ripple reduction technology", which are not used in conventional electrical current feedback control. Variation compensation technology uses the signals of a failure monitoring sensor to compensate fluctuation in parameters such as resistance caused by variation in temperature and so on, while torque ripple reduction technology compensates the interphase resistance unbalance in three-phase. Details are given below.

2. 1 Basic Configuration of Electrical Current Open-loop Control

Figure 3 shows the motor model for a three-phase brushless motor, while equation (1) shows the circuit equation for this motor model[4].

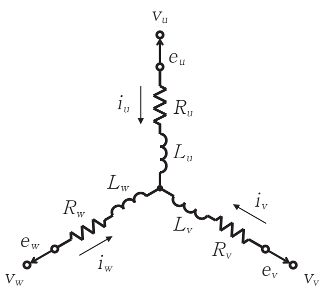

Fig. 3 Motor model

Here,
v_u. v_v. v_w : U, V, W phase armature voltage
i_u, i_v, i_w : U, V, W phase armature current
R_u, R_v, R_w : U, V, W phase armature resistance
L_u, L_v, L_w : U, V, W phase armature self- inductance
e_u, e_v, e_w : Speed electromotive force created in U, V, W phase armature by a permanent magnetic field

$$\begin{cases} v_u = (R_u + \frac{3}{2}PL_u) \times i_u + e_u \\ v_v = (R_v + \frac{3}{2}PL_v) \times i_v + e_v \\ v_w = (R_w + \frac{3}{2}PL_w) \times i_w + e_w \end{cases} \quad (1)$$

Here, P: Differential operator (= d/dt)

The following equation will be created if this is converted into a dq axis reference system.

$$\begin{cases} v_d = (R + PL_d) \times i_d - \omega \cdot L_q \cdot i_q \\ v_q = (R + PL_q) \times i_q + \omega \cdot L_d \cdot i_d + \omega \cdot K_e \end{cases} \quad (2)$$

Here,
v_d, v_q : dq axis armature voltage
i_d, i_q : dq axis armature current
R : dq axis armature resistance (Ideally, $R = R_u = R_v = R_w$)
L_d, L_q : dq axis armature self- inductance
ω : Motor angular speed
K_e : Speed electromotive force constant

Open-loop control is when the i_d, i_q of equation (2) are made i_d*, i_q* then substituted with the motor angular speed detected in ω and the instruction voltage of v_d, v_q is calculated. Here, the values of R, K_e differ due to variation between individual parts and temperature fluctuation. Moreover, the resistance values of each phase, R_u, R_v, R_w will differ to the R value depending on the circuit and join with the motor. That compensation technology is shown below.

2. 2 Variation Compensation Technology

In the motor control equation used in open-loop control, resistance R and speed electromotive force constant K_e have performance variation of each part and vary due to environmental temperature. As a result, control error occurs and it becomes impossible to output motor torque of good accuracy. Particularly in the case of EPS, the environmental temperature varies widely from –40°C to +85°C and this error significantly affects control accuracy. **Figure 4** shows examples of the variation in resistance and speed electromotive force constant due to temperature.

Therefore, the motor current value detected from the signal of a failure monitoring sensor in the drive circuit is used, as shown in **Fig. 2(b)**. This failure monitoring sensor detects motor current value i_{qd} at appropriate timing which were used to develop a technology to compensate R and K_e. This technology made it possible to support the gradual variation of R and K_e.

$$R' = \frac{v_q - \omega \cdot L_d \cdot i_d^* - \omega \cdot K_e}{i_{qd}} \quad (3)$$

$$K_e' = \frac{v_q - \omega \cdot L_d \cdot i_d^* - R \cdot i_{qd}}{\omega} \quad (4)$$

Here, R' and K_e' are the values after R and K_e are compensated.

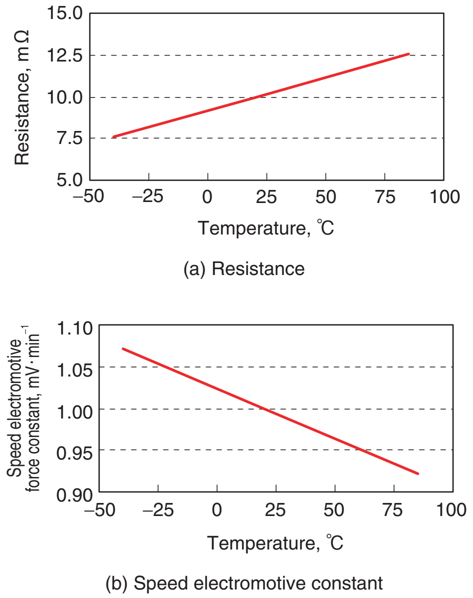

Fig. 4 Variations according to temperature

2. 3 Torque Ripple Reduction Technology

When post-compensation value R', K_e', target current values i_d*, i_q* and motor angular speed ω are substituted into equation (2), dq axis armature voltage v_d*, v_q* can be calculated using formula (5).

$$\begin{cases} v_d^* = (R' + PL_d) \times i_d^* - \omega \cdot L_q \cdot i_q^* \\ v_q^* = (R' + PL_q) \times i_q^* + \omega \cdot L_d \cdot i_d^* \\ \qquad + \omega \cdot K_e' \end{cases} \tag{5}$$

When this formula (5) is separated into resistance R' and all other terms (formula (6)) then substituted into formula (7), which converts from dq axis to three-phase voltage, the commands of u, v, w armature voltage v_u*, v_v*, v_w* can be found in formula (8).

$$\begin{cases} v_d^* = R' \times i_d^* + v_{da} \\ v_q^* = R' \times i_q^* + v_{qa} \end{cases} \tag{6}$$

Here, $\begin{cases} v_{da} = PL_d \times i_d^* - \omega \cdot L_q \cdot i_q^* \\ v_{qa} = PL_q \times i_q^* + \omega \cdot L_d \cdot i_d^* + \omega \cdot K_e' \end{cases}$

$$\begin{cases} v_u^* = \sqrt{\frac{2}{3}}\,(v_d^* \times \cos\theta - v_q^* \times \sin\theta) \\ v_v^* = \sqrt{\frac{2}{3}}\left[v_d^* \times \cos\left[\theta - \frac{2}{3}\pi\right] - v_q^* \times \sin\left[\theta - \frac{2}{3}\pi\right]\right] \\ v_w^* = \sqrt{\frac{2}{3}}\left[v_d^* \times \cos\left[\theta + \frac{2}{3}\pi\right] - v_q^* \times \sin\left[\theta + \frac{2}{3}\pi\right]\right] \end{cases} \tag{7}$$

$$\begin{cases} v_u^* = \sqrt{\frac{2}{3}}\,(R' \cdot (i_d^* \times \cos\theta - i_q^* - \sin\theta) + v_{da} \times \cos\theta - v_{qa} \times \sin\theta) \\ v_v^* = \sqrt{\frac{2}{3}}\left[R' \cdot \left[i_d^* \times \cos\left[\theta - \frac{2}{3}\pi\right] - i_q^* \times \sin\left[\theta - \frac{2}{3}\pi\right]\right] + v_{da} \times \cos\left[\theta - \frac{2}{3}\pi\right] - v_{qa} \times \sin\left[\theta - \frac{2}{3}\pi\right]\right] \\ v_w^* = \sqrt{\frac{2}{3}}\left[R' \cdot \left[i_d^* \times \cos\left[\theta + \frac{2}{3}\pi\right] - i_q^* \times \sin\left[\theta + \frac{2}{3}\pi\right]\right] + v_{da} \times \cos\left[\theta + \frac{2}{3}\pi\right] - v_{qa} \times \sin\left[\theta + \frac{2}{3}\pi\right]\right] \end{cases} \tag{8}$$

Here, if the equation is changed so that the R' of each phase becomes the resistance of each phase, R_u, R_v, R_w then equation (9) will be formed. In other words, by multiplying R' of equation (8) with the ratio of each phase resistance, it is possible to compensate the resistance variation of each phase therefore, using this equation, motor torque of a good accuracy can be outputted.

$$\begin{cases} v_u^* = \sqrt{\frac{2}{3}}\left[R' \cdot \frac{R_u}{R'} \cdot (i_d^* \times \cos\theta - i_q^* - \sin\theta) + v_{da} \times \cos\theta - v_{qa} \times \sin\theta\right] \\ v_v^* = \sqrt{\frac{2}{3}}\left[R' \cdot \frac{R_v}{R'} \cdot \left[i_d^* \times \cos\left[\theta - \frac{2}{3}\pi\right] - i_q^* \times \sin\left[\theta - \frac{2}{3}\pi\right]\right] + v_{da} \times \cos\left[\theta - \frac{2}{3}\pi\right] - v_{qa} \times \sin\left[\theta - \frac{2}{3}\pi\right]\right] \\ v_w^* = \sqrt{\frac{2}{3}}\left[R' \cdot \frac{R_w}{R'} \cdot \left[i_d^* \times \cos\left[\theta + \frac{2}{3}\pi\right] - i_q^* \times \sin\left[\theta + \frac{2}{3}\pi\right]\right] + v_{da} \times \cos\left[\theta + \frac{2}{3}\pi\right] - v_{qa} \times \sin\left[\theta + \frac{2}{3}\pi\right]\right] \end{cases} \tag{9}$$

3. Experiment Results

The motor speed – torque characteristic which is common used to evaluate motor charactaristic was measured at varying temperatures. First, **Fig. 5** shows the measurement results at 85℃. In case of general open-loop control which did not compensate R and K_e was used, the torque error increased at low motor speed, on the other hand when control which compensates R and K_e was used, an error of 0.6%, practically the same as the theoretical value found by considering the temperature characteristic, was able to be outputted. This is also the case at –40°C, as shown in **Fig. 6**, where output results were obtained which were practically in agreement with the theoretical values.

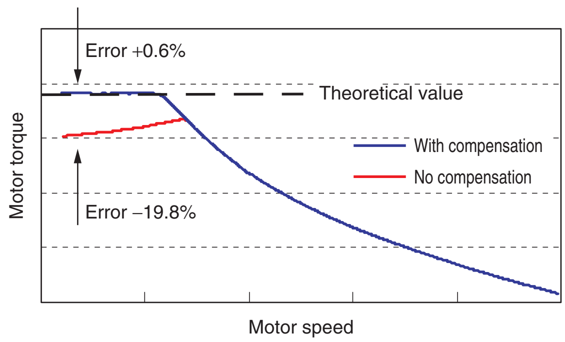

Fig. 5 Motor characteristics at 85℃

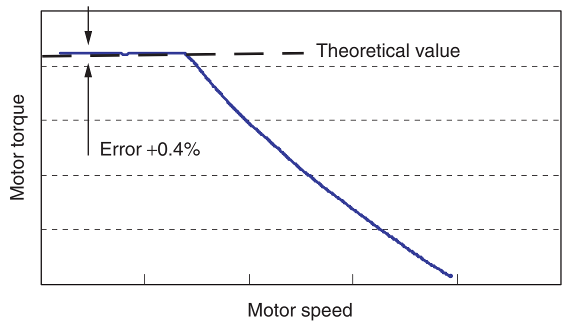

Fig. 6 Motor characteristics at –40℃

Next, in order to investigate the effect of the difference in ineach phase resistance, the torque characteristic depending on rotor position of motor was measured. The results are shown in **Fig. 7** and show that if the variation in individual phase resistance is not compensated, a large torque error of 13.0% occurs, however, when compensation was performed, it was possible to reduce this error to less than 2%, which is not affect steering feeling for a driver.

In the abovementioned way, conventionally it was not possible to output motor torque of a good accuracy due to the effect of temperature, etc., however, by the new variation compensation technology and torque ripple reduction technology, the developed open-loop control which can be applied to EPS has been established. As shown in **Fig. 8**, by using this control , motor torque is improved compared to that of conventional feedback control, and it is possible to downsize the motor controller (lightweight design) by around 10%.

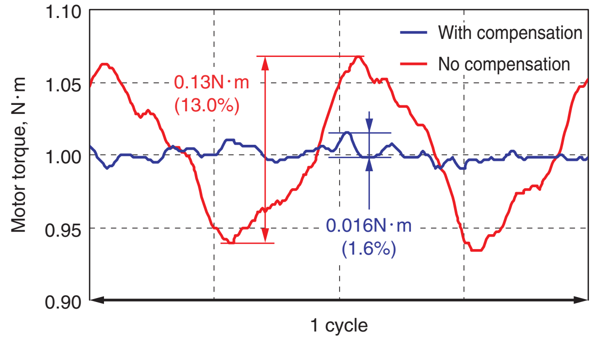

Fig. 7 Motor torque amplitude by rotor position

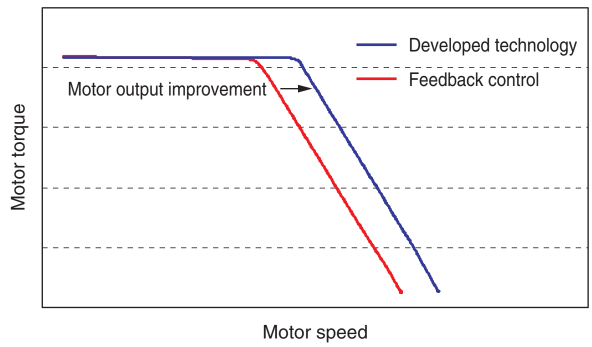

Fig. 8 Comparison of motor outputs

4. Conclusion

In regards to the issue of motor output reduction associated with conventional current feedback control, by developing an original current open-loop control in which the current sensor has been abolished, it was possible to significantly improve the features of brushless motors, namely downsizing and high output. Moreover, the issue of torque accuracy, specific to open-loop control was also improved through our original technology, achieving a high output brushless motor current control also able to support EPS. Given that application on EPS systems, which are used in harsh environments, is now possible, potential towards other applications can be anticipated. JTEKT will continue to accumulate downsizing and weight reduction design technologies including motors and circuits with the aim of improving products.

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