Development of Brushless Motor EPS Assist Control for Disconnection Failure

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When failure occurs in an electric component of an electric power steering (EPS) system, measures are taken to stop assist control. After the failure occurs, EPS results in no assist. In such a case, the driver must steer the vehicle by torque only, which places a burden on the driver. In order to alleviate this burden, we have developed EPS assist control for a failure in which only one of the three phases is unable to supply power to a motor in the brushless motor EPS.

Key Words*: steering system, EPS, brushless motor, functional safety*

1. Introduction

Electric power steering (EPS), being able to contribute to improved fuel efficiency, has been rapidly spreading in the market as a result of increased consciousness of environmental issues. EPS was originally introduced for light vehicles whose load on the front shaft, or so-called rack force, is small. At present, EPS is being adopted also for medium and large size vehicles as well in accordance with the improved assist output.

Meanwhile, ISO26262 has been specified for functional safety and, therefore, assessment for analysis, design and manufacturing has been required on the safety for electronic control systems. Among them, analyses are required on the effect when EPS fails. At the time of failure, EPS changes to the safety mode by stopping the assist output after intercepting the effect caused by the failure. As a result, that creates the condition where drivers are burdened due to the increase of steering torque of drivers by losing the assist output.

The main purpose of this development is the reduction of the burden imposed on drivers by supplying the assist output as continuously as possible even after such a failure occurs. In this report, on brushless motor EPS, even in case of electric power supply to a motor becoming impossible through one phase only out of three phases due to breaking lines to the motor, etc., the control method of continuously supplying the steering torque assist is herewith introduced.

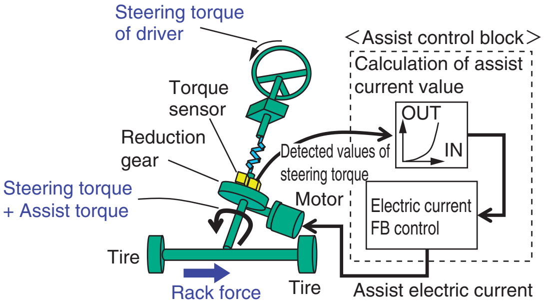

Fig. 1 Schematic diagram of EPS assist control method

2. EPS Assist Control

EPS is a system in which assist torque from a motor is provided in accordance with steering torque in order to alleviate the steering torque of driver for rack force (**Fig. 1**). When a driver steers, the steering torque amount is detected by a torque sensor. In accordance with the value detected by the torque sensor, the assist current value is calculated. The assist torque is generated by providing electric current to the motor in accordance with this assist current value. The steering torque of the driver is alleviated by this assist torque (**Fig. 2**).

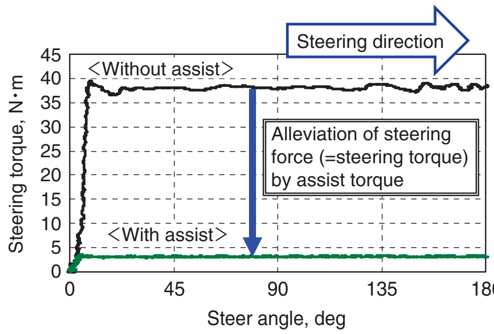

Fig. 2 Conditions of steering torque and assist torque at the time of steering

3. Conductivity Method for Brushless Motor

For the brushless motor that generates the assist torque or the motor torque, each phase of the driving circuit of the motor is electrified in accordance with the equation (1).

$$\begin{pmatrix} I_u \\ I_v \\ I_w \end{pmatrix} = -\sqrt{\frac{2}{3}} \times I_q \times \begin{pmatrix} \sin\theta_e \\ \sin(\theta_e + 120) \\ \sin(\theta_e - 120) \end{pmatrix} \quad \cdots(1)$$

I_u : U-phase current [A]
I_v : V-phase current [A]
I_w : W-phase current [A]
I_q : Assist current [A]
θ_e : Motor electric angle [deg]

The brushless motor can generate assist torque in accordance with the fixed assist current by changing the amount of electric current for each phase depending on the position of the motor electric angle (**Fig. 3**).

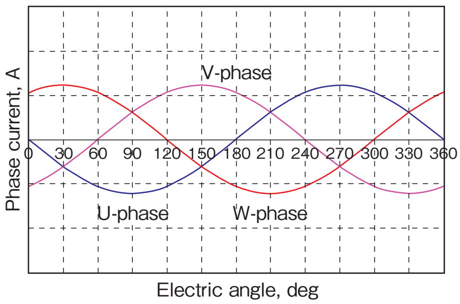

Fig. 3 Conductivity method for each phase of brushless motor (during normal operation)

4. Failure on Driving Part of Brushless Motor

The driving portion of the brushless motor generally consists of an inverter (MOS FET × 6 pieces), pre-driver, shut off path, motor line harness & connecter and electric current sensor (**Fig. 4**). Thus, the driving portion of the brushless motor consists of many parts and is sometimes electrified with a large amount of electric current (over 50 ampere), and, therefore, failure occurrence cannot be neglected. So far, in the case that the electric power supply has stopped to one phase out of three phases due to such troubles as the open failure of MOS FET or line disconnection failure on motor line (between inverter and motor), the assist output stops.

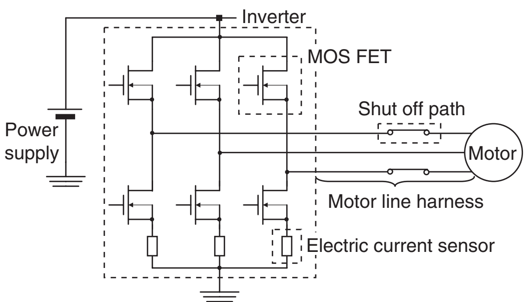

Fig. 4 Circuit diagram from electric power supply to motor

5. Assist Control at Time of One Phase Disconnection Failure

5. 1 Conductivity Method at Time of One Phase Disconnection Failure on Driving Portion of Brushless Motor

As a conductivity method of the brushless motor enabling output of the motor torque at the time of disconnection failure on one phase, in case disconnection failure occurs on U-phase as an example, equation (4) is derived from energy relation equation (2) of rotor and stator on a brushless motor and U-phase disconnection condition equation (3).

$$T \times \left(\omega \times \frac{\pi}{180}\right) = I_u \times V_u + I_v \times V_v + I_w \times V_w \quad \cdots(2)$$

$$I_u = 0, \quad I_v + I_w = 0 \quad \cdots(3)$$

T : Motor torque [N·m]
ω : Motor angle speed [deg/s]
V_u : U-phase voltage [V]
V_v : V-phase voltage [V]
V_w : W-phase voltage [V]

$$I_u = 0, \quad I_v = \frac{I_q}{\sqrt{2} \times \cos\theta_e}, \quad I_w = \frac{-I_q}{\sqrt{2} \times \cos\theta_e} \quad \cdots(4)$$

Even in the case a failure occurs, motor torque can be obtained with almost the same amount of motor torque as before failure occurrence (**Fig. 6**) by supplying electric current to the V-phase and the W-phase in accordance with equation (4) (**Fig. 5**). However, under the electric angles of 90 deg. and 270 deg., an infinite amount of electric current is required.

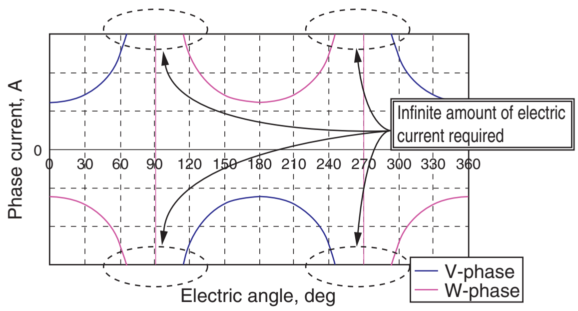

Fig. 5 Conductivity method for each phase of brushless motor (when U-phase fails)

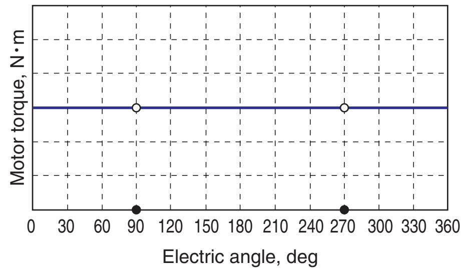

Fig. 6 Motor torque when U-phase fails

5. 2 Problem of Conductivity Method at Time of One Phase Disconnection Failure

Actually, as it is necessary to restrict the amount of the electric current to the motor of each phase because of the existence of rated current in a motor, it is impossible to supply an infinite amount of electric current to the motor. In other words, the amount of electric current to the motor of each phase is restricted. That is, the output torque of the motor is restricted as a result and the shortage of assist torque occurs on some areas (**Fig. 7**). In order to steer, it is necessary (under those areas with the shortage of assist torque) to supplement the steering torque to large extent on the electric angle areas (electric angle at about 90 deg. and about 270 deg.) as shown in **Fig. 7**, which results in problems such as sudden change of steering torque with stick feeling.

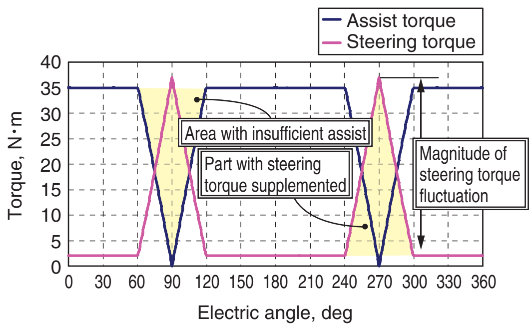

Fig. 7 Assist torque and steering torque when current is restricted

6. Measures for Conductivity Method at Time of One Phase Disconnection Failure

For the problem above, when calculating the command values of electric current for each phase, measures have been taken to adjust the phase of the electric angle by degree α (Equation (5)) (**Fig. 8**).

$$I_u = 0,\ I_v = \frac{I_q}{\sqrt{2} \times \cos(\theta_e + \alpha)}$$

$$I_w = \frac{-I_q}{\sqrt{2} \times \cos(\theta_e + \alpha)} \quad \cdots(5)$$

α [deg]: Amount of electric angle phase adjustment

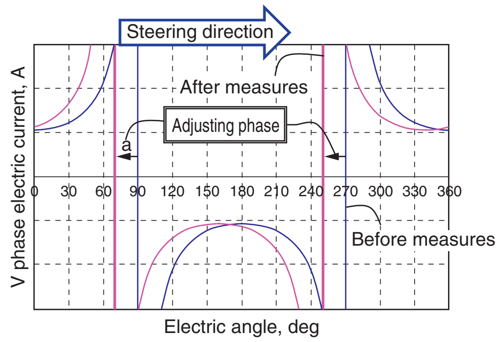

Fig. 8 Motor conductivity method before and after measures are taken

As a result of conductivity in accordance with the above method, compared with the motor torque before the measures, the area where the assist is large (A area) and the area where adverse torque occurs (B area) occur on the motor torque after the measures (**Fig. 9**). Under the A area, the energy can be saved in the motor rotational motion and the motor rotational speed can be increased. Under the B area, even with insufficient power on the motor rotation and not enabling to exceed the assist zero point, the measures can force the motor to rotate adversely against the steering direction resulting in returning again to the A area. From the above, energy is saved on the A area to enhance the motor rotational speed and, if the power becomes insufficient under the B area, the motor rotational speed can be enhanced further again after returning to the A area. By repeating these operations, it becomes possible to exceed over the assist zero point which results in reducing the stick feeling by drivers.

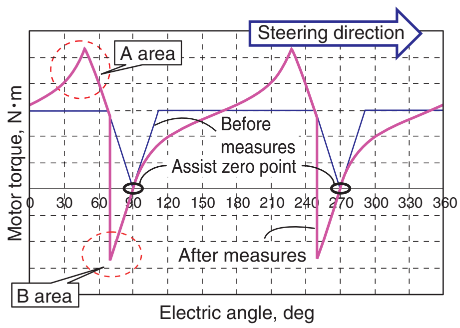

Fig. 9 Motor torque before and after measures are taken

7. Result of Verification with Actual Machine

The electric angles of 990 deg., 1 170 deg. and 1 350 deg. in **Fig. 10** are equivalent to the assist zero point. When steered to a certain direction (from the left to the right in **Fig. 10**), it can be found that the motor angle proceeds toward the steering direction after the motor rotates until a certain speed of motor rotation at the assist zero point. As seen in **Fig. 11**, compared with the conventional EPS at time of the assist stop, the steering torque becomes smaller, which explains that the burden of drivers has been alleviated. Also as shown in **Fig. 12**, by the vibration occurring at time of steering, drivers can get information of failure occurrence and, accordingly, an effect for detecting abnormalities can be expected.

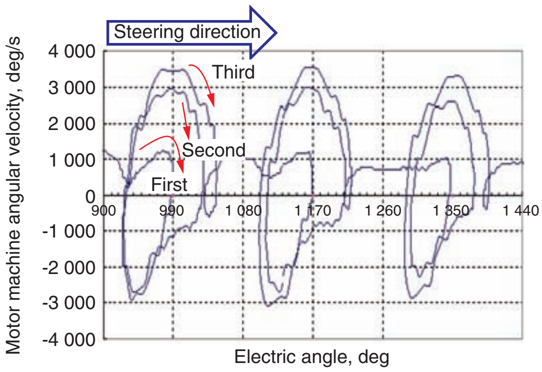

Fig. 10 Motor rotation when assist continues (when U-phase fails)

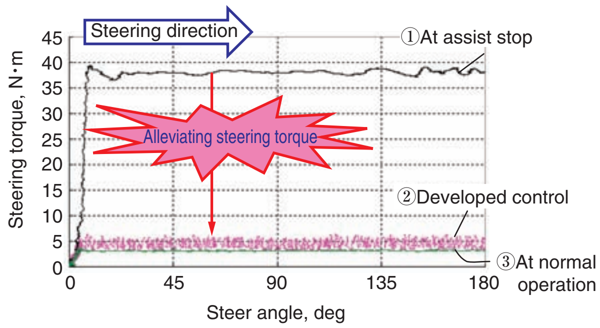

Fig. 11 Results of effect verification

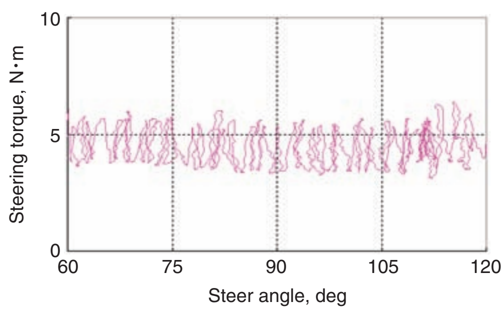

Fig. 12 Steering torque when assist continues (enlarged view of **Fig. 11**)

8. Conclusion

In this report, we have discussed a brushless motor EPS whereby EPS assist control can continue the assist even when the electric power supply has stopped to one phase out of three phases of brushless motor. Hereafter, it is forecasted that EPS will come to be installed in large cars. Therefore, from the viewpoint of alleviating the burden of drivers at time of failures, further development is expected for technology of continuing the assist at time of failures on the over-all systems of EPS.


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