Experimental Verification of Vector Controlled Magnetically Modulated Motor

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I. Introduction

This paper focuses on vector control of a magnetically modulated motor (MMM). The structure of this motor is quite different from a standard PMSM because it has two output shafts, i.e., an outer magnetic flux modulator and an inner PM rotor. There have been several studies regarding the optimum design of the motor, but the vector control using an actual machine is still unexplored [1]. Therefore, this paper discusses the control algorithm and examines its performance with a prototype MMM.

II. Prototype and Experimental Setup

The MMM has relationship of the pole pair number ratios of the stator, the inner PM rotor, and the outer modulator, i.e., $P_s : P_{pm} : P_{mod} = n : 2n : 3n$ (n is a natural number). The stator pole pair number is different from that of the inner rotor in the MMM, which is the most important feature as compared with common PM motors. The prototype has been made with $n = 4$.

The test prototype MMM is shown in Fig. 1. The motor is placed in the middle between the two torque-meters placed on either end of the rotor shafts. Two load motors assuming the drive shaft and the engine are mechanically connected through the torque meters, respectively. Fig. 2 shows a vector control block diagram for the prototype. Two resolvers are used to detect the positions of the two rotors. The current and phase angle are given as command values to perform the vector control. The DC bus voltage is 80 V and the PWM frequency is 10 kHz. The angular displacement of the two rotors are related to the stationary reference frame as

$$\theta = \omega t = P_{mod}\omega_{mod}t - P_{pm}\omega_{pm}t = \theta_{mod} - \theta_{pm} . \qquad (1)$$

The two-axis voltage equation used for the vector control is given by

$$\begin{bmatrix} v_\gamma \\ v_\delta \end{bmatrix} = \begin{bmatrix} R+pL & -\omega L \\ \omega L & R+pL \end{bmatrix} \begin{bmatrix} i_\gamma \\ i_\delta \end{bmatrix} + \begin{bmatrix} -E_\gamma \\ \omega\sqrt{\dfrac{3}{8}}\dfrac{L_{ac}\mathcal{F}}{N} - E_\delta \end{bmatrix}, \qquad (2)$$

$$\because \omega = P_{mod}\omega_{mod} - P_{pm}\omega_{pm}$$

where E_γ and E_δ are voltages due to asynchronous components. On the other hand, the torque is given by

$$\tau_s = \frac{P_s}{P_{pm}}\tau_{pm} = -\frac{P_s}{P_{mod}}\tau_{mod} . \qquad (3)$$

III. Experimental Test Results

Through the experimental tests, the following three driving modes are examined, assuming a HEV operation: 1) engine assist mode; 2) EV mode, and 3) regeneration mode. In each driving mode, the following are checked: 1) relationship between the torque and the gear ratio, and 2) torque-current phase characteristics.

Fig. 3 shows the torque-δ-axis current characteristics. Here the current norm is fixed at a constant value of 90 A, and γ-axis current is kept at zero and δ-axis current is varied. It is confirmed from the graph that the torque of the inner rotor and the torque of the outer modulator are proportional to δ-axis current regardless of the driving modes, which satisfies (3). Fig. 4 shows the torque-current phase β characteristics. Here β is varied while the current norm is also kept at constant value. Both of the rotors deliver their torque, keeping the gear ratio defined by (3) regardless of the β change.

IV. Conclusion

This paper discussed the vector control of a magnetically modulated motor, and various aspects of the motor have been verified by simulating the three HEV driving modes.

References

[1] Y. Takeuchi, H. Kato, M. Tago, S. Ogasawara, and H. Sakai, "Operating Principle and Control Method of the Magnetic Modulated Motor," *IEEJ National Convention Record*, No.5-041, 2013, pp. 73-74.

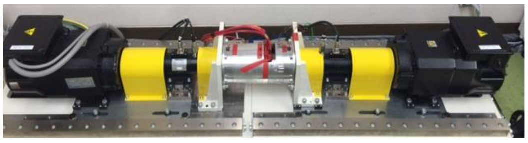

Fig. 1. Experimental setup.

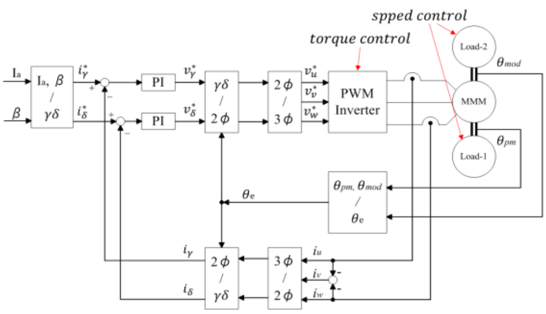

Fig. 2. Block diagram of vector control.

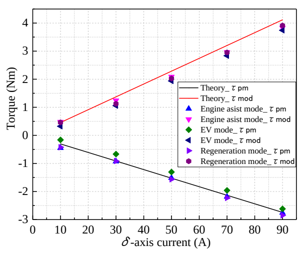

Fig. 3. T-i_δ characteristics.

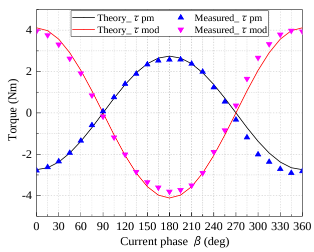

Fig. 4. T-β characteristics.