Study on Inductance Parameter compensation method for flux-torque control of IPMSM

Hyun-Jo Pyo[1], Dong-Ho Kim[2]. Min-Jae Jeong[1], In-Jun Yang[2], Si-Woo Song[2] and Won-Ho Kim[1]

[1]Department of Electrical Engineering, Gachon University, Seongnam 13120, Korea
[2]Department of Electrical Engineering, Hanyang University, Seoul 04763, Korea

Due to the importance of environmental issues, one of the global issues, the use of permanent magnet synchronous motors has increased significantly in many industries. Motor efficiency is important due to environmental regulations. As a method of increasing the efficiency of a motor, there is a method of increasing the efficiency through a motor design. Although the design is important, the method of controlling the actually developed motor also greatly affects the efficiency. As a method of controlling the existing motor, current control was performed. Speed-torque control is widely used as a method commonly used in conventional motor control. As the motor control method proposed in this paper, flux-torque control was used. Flux-torque control is not a new technology, but in the case of the control method proposed in this paper, a method of interpolating of values after comparison with actual data through finite element analysis (FEA) of the motor is applied. In this paper, a method for interpolating of inductance among important factors for motor torque control is proposed. Therefore, in the case of the proposed flux-torque control, the validity of the study was verified based on the actual data from the FEA and the actual manufactured motor shape

***Index Terms*— Interior Permanent Magnet Synchronous Motor (IPMSM), flux-torque control, look-up table, Inductance curve fitting, Flux linkage fitting**

I. INTRODUCTION

IN THE CASE OF speed-torque control, which is widely used in the existing current control, it has the advantage of excellent torque control characteristics by creating a current-map for each rotation speed and voltage of the motor [1] – [4]. However, in the case of speed-torque control, since it is a method made from DC voltage, it requires a lot of testing after production to extract data for each voltage in order to control it in consideration of voltage fluctuations. However, in the case of flux-torque control, unlike the principle of speed-torque control, there is no need to prepare a current-map for each voltage, so it does not take much time for testing. However, there is a disadvantage in that the value of the flux estimator needs to be adjusted, so that it is necessary to properly respond to voltage fluctuations for each driving area. In this paper, flux-torque control was performed based on the magnetic flux extracted from the electromagnetic analysis value. In this paper, a method of interpolating of inductance values, an important factor, was proposed to create a flux-torque control look-up table.

II. TORQUE CONTROL METHOD

In the case of existing torque control, flux linkage was estimated through actual test production, and data for each current was extracted and used for torque control of the motor. In this paper, the flux-torque control look-up table used for motor control is designed based on electromagnetic analysis. There is no need to calculate flux linkage for each speed if torque control is performed by creating a look-up table based on electromagnetic analysis. In the case of flux linkage, since it is a value that includes speed and voltage, it has the advantage that it is not necessary to proceed through testing by voltage and speed. Therefore, the values of inductance and voltage through electromagnetic analysis are important factors. There is a five key point test in the electromagnetic field-based flux-torque control look up table model. The five important points here are the zero current data and four points are maximum current at maximum torque current phase angle degree data. Figure 1 shows the data of five points for inductance compensation.

Is	Beta	Tq	Vd	Vq
580	0	155.51	-121.81	68.36
580	42.0	243.93	-128.26	13.37
580	90	-1.03	-20.38	-40.74
580	138.5	-256.71	98.98	-16.01
0	0	-1.37	-0.98	61.62

Fig. 1. Five points data of inductance compensation.

Referring to Figure 1, a four-point test was performed at maximum current and one test was performed at 0A. The current phase angle degree at maximum current is β = Beta. The reason for the test at 0 degree of the current phase angle degree here is that the L_{qs} inductance value of the Interior Permanent Magnet Synchronous Motor (IPMSM) can be known. Equation (1) defines the value of L_{qs} .

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$$v_{ds}^r = R_s i_{ds}^r + L_{ds}\frac{di_{ds}^r}{dt} - \omega_r L_{qs} i_{qs}^r$$
$$v_{ds}^r = R_s i_{ds}^r - \omega_e L_{qs} i_{qs}^r \qquad (1)$$
$$L_{qs} = \frac{(v_{ds}^r - R_s i_{ds}^r)}{-\omega_e i_{qs}^r}$$

The reason for testing at 90 degree in figure 1 is that the value of L_{ds} could be known, and equation (2) defines L_{ds}.

$$v_{qs}^r = R_s i_{qs}^r + L_{qs}\frac{di_{qs}^r}{dt} + \omega_r (L_{ds} i_{ds}^r + \phi_f)$$
$$v_{qs}^r = R_s i_{qs}^r + \omega_e L_{ds} i_{ds}^r + \omega_m K_e \qquad (2)$$
$$L_{ds} = \frac{v_{qs}^r - R_s i_{qs}^r - \omega_m K_e}{\omega_e i_{ds}^r}$$

And the current phase angle degree 42 and 138.5 are the current phase angle degree values that generate the maximum torque..

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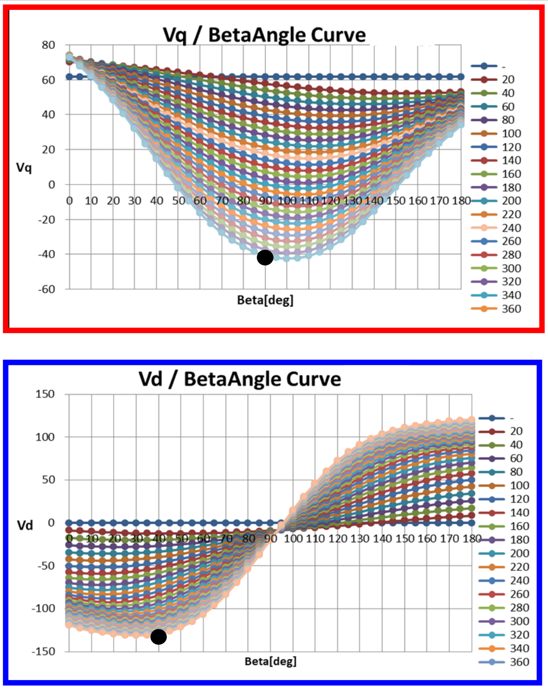

Fig. 2. Vd and Vq measurement point.

Figure 2 shows the measurement point of v_{ds}^r, v_{qs}^r. v_{ds}^r has a minimum value in the MTPA driving region. Therefore, if v_{ds}^r is compensated, the ratio between the analyzed value and the actual measured value is calculated and reflected. v_{qs}^r has a minimum value at current phase angle degree 9. Therefore, the measurement point was selected as 90 degree for further compensation. Looking at the above equations (1) and (2), it can be seen that the inductance has an infinite value when the current phase angle value is 0, 90degree. Figure 3 shows the measurement points of L_{qs}, L_{ds}. In Figure 3, red color shows the L_{qs} measurement point at 0 degree, and blue color shows the L_{ds} measurement point at 90 degree.

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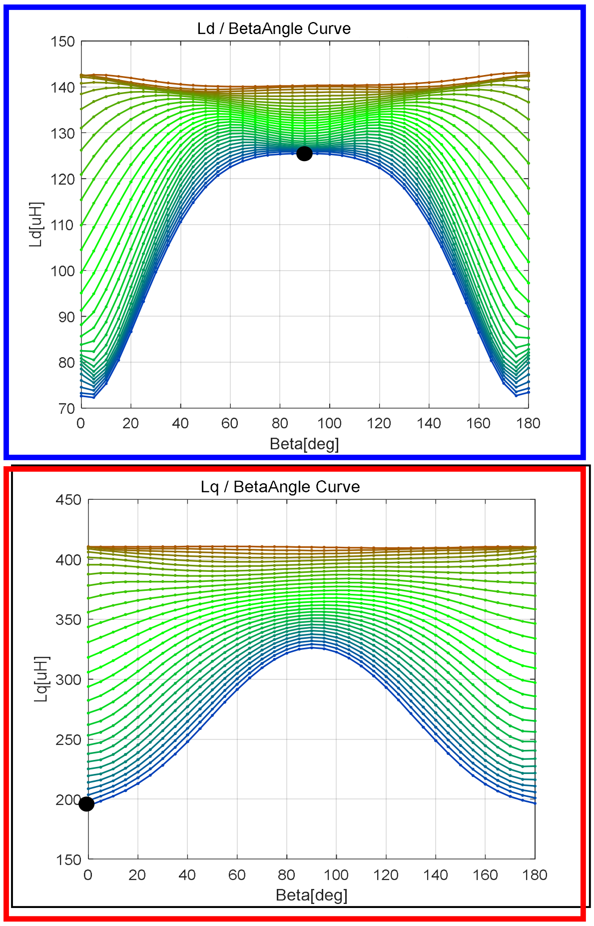

Fig. 3. Inductance measurement point.

III. Compensation of Parameters

A. Inductance compensations

For precise control, the inductance value should be compensated. First, the L_{ds} value is compensate as in equation (3).

$$L_{ds \cdot offset} = \frac{L_{ds \cdot measure} I_{\max} \angle 90}{L_{ds \cdot FEA} I_{\max} \angle 90} \tag{3}$$

The compensated L_{ds} value, it is derived as the value of $L_{ds \cdot FEA} + L_{ds \cdot offset}$. If the above equation (3) is written in the current and current phase angle degree table, it is shown in Figure 4.

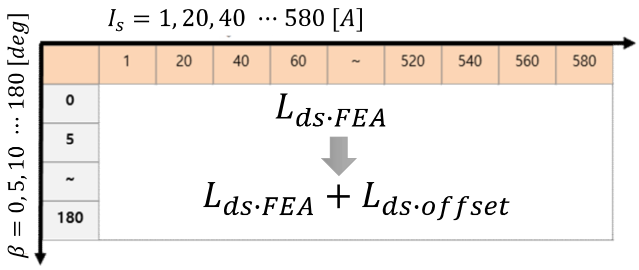

Fig. 4. D-axis inductance compensation.

Compensate the L_{qs} value in the same process. In the case of L_{qs}, the current phase angle is 0 degree. Equation (4) shows the value L_{qs} of compensation, and Figure 5 is the way Equation (4) is written in the current and current phase angle degree table..

$$L_{qs \cdot offset} = \frac{L_{qs \cdot measure} I_{\max} \angle 0}{L_{qs \cdot FEA} I_{\max} \angle 0} \tag{4}$$

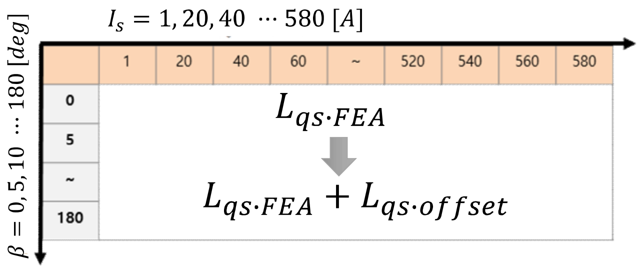

Fig. 5. Q-axis inductance compensation.

B. Voltage compensation

First, to compensate for v_{ds}^r, you need to know the FEA analysis result and the actual measured data value. In case of v_{ds}^r, the MTPA point at the maximum current was measured through the MTPA driving range test. Therefore, the compensation value of v_{ds}^r is the same as Equation (5). And the compensation value of v_{ds}^r is written in the current and current phase angle degree table as shown in Figure 6.

$$Gain\_v_{ds}^r = \frac{v_{ds \cdot measure}^r I_{\max} \angle \beta_{MTPA}}{v_{ds \cdot FEA}^r I_{\max} \angle \beta_{MTPA}} \tag{5}$$

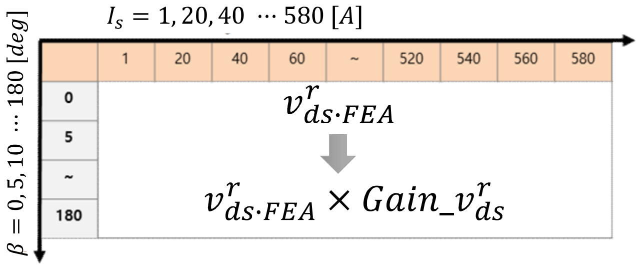

Fig. 6. D-axis voltage compensation.

Unlike the compensation of v_{ds}^r, v_{qs}^r should compensate the measured value of 0A as well. Therefore, the measured value of 0A is defined by offsetting v_{qs}^r, and the formula for removing the offset is defined again. In Equation (6), we define the compensation of v_{qs}^r.

$$Gain\_v_{qs}^r = \frac{v_{ds \cdot measure}^r I_{\max} \angle \beta_{MTPA} + offset(= v_{qs\_FEA\_\min}^r)}{v_{ds \cdot FEA}^r I_{\max} \angle \beta_{MTPA} + offset(= v_{qs\_FEA\_\min}^r)} \tag{6}$$

The compensation value of v_{qs}^r was written in the current and current phase angle degree table as shown in Figure 7.

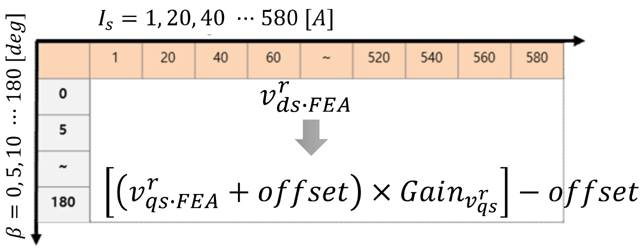

Fig. 7. Q-axis voltage compensation.

In Figure 8, the voltage after compensation and the actual result graph were compared. The result of Figure 8 shows that the voltage of the actual measured value and the interpolted voltage waveform are almost identical without error. This means that there is almost no error in inductance.

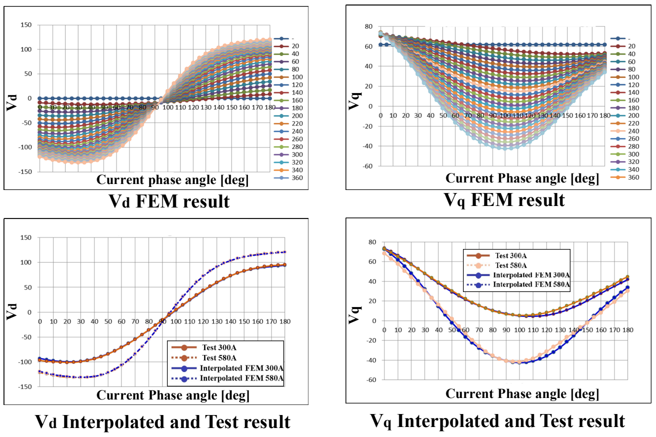

Fig. 8. Comparison voltage compensation result and test result.

C. Comparison Flux Data

Previously, inductance and voltage were compensated through FEA analysis values and actual measurement data. Therefore, if the flux linkage is written in the current and current phase angle degree table through the compensated value, it is shown in Figure 9.

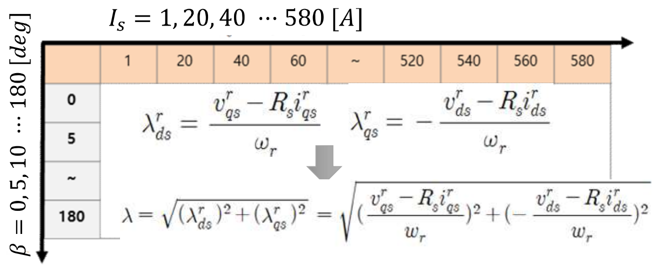

Fig. 9. Flux linkage after inductance and voltage compensation.

Therefore, the graph of the final compensated flux linkage is shown in Figure 10.

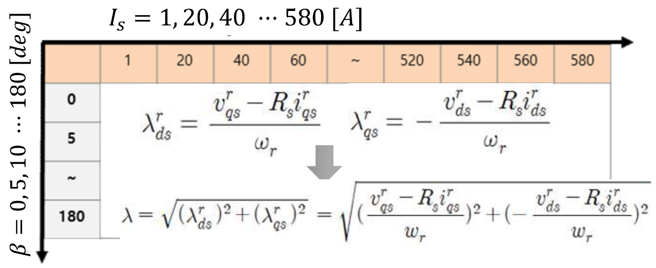

Fig. 10. Flux linkage after inductance and voltage compensation.

Since the existing voltage value is almost similar to the actual data, it was confirmed that the graph of flux linkage also has almost similar values as shown in Figure 11.

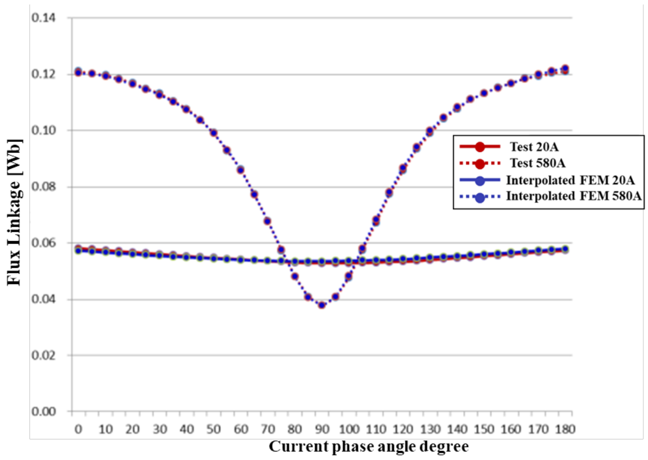

Fig. 11. Flux linkage after inductance and voltage compensation.

D. Torque Compensation

In the motor, the above procedure was performed to control the actual torque. Therefore, the final torque compensation method is shown in Figure 12 and defined in Equation (7).

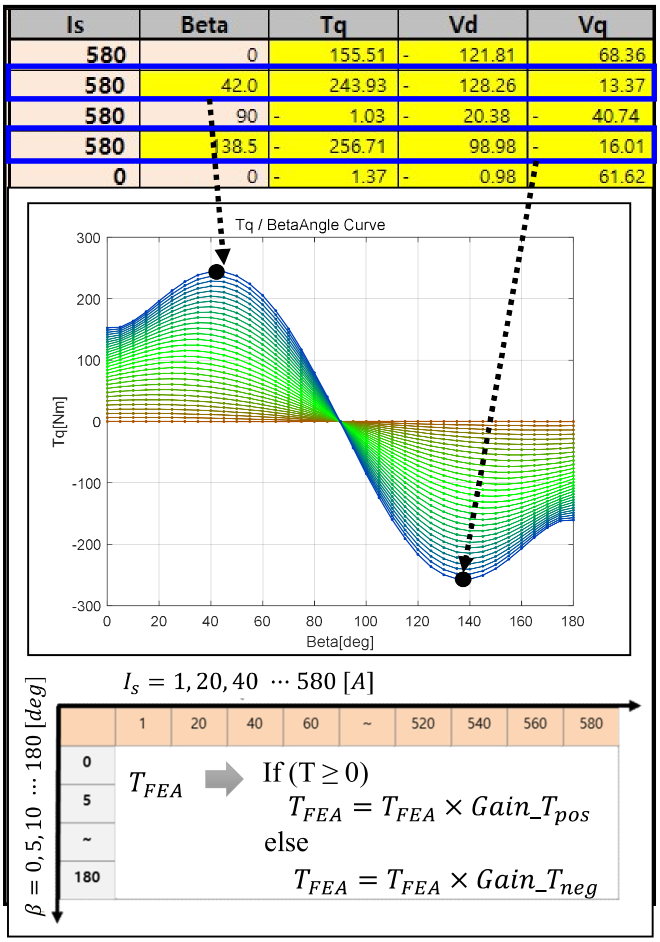

Fig. 12. Torque compensation.

$$Gain\_T_{pos} = \frac{T_{pos\_measure} I_{\max} \angle \beta_{pos\_MTPA}}{T_{pos\_FEA} I_{\max} \angle \beta_{pos\_MTPA}}$$
$$Gain\_T_{neg} = \frac{T_{neg\_measure} I_{\max} \angle \beta_{neg\_MTPA}}{T_{neg\_FEA} I_{\max} \angle \beta_{neg\_MTPA}} \quad (3)$$

IV. Test Result

Table Ⅰ shows the specifications of the EV motor.

TABLE I
Motor Specification

Value	Target	Unit
Max. Power	65	kW
Power	36.8	kW
Max. Torque	240 @0~2,580rpm 47.7 @13,000rpm	Nm
Torque	136.2 @ 2,580rpm 70.2 @5,000rpm 27 @13,000rpm	Nm
Base RPM	2,580	RPM
Max. RPM	13,000	RPM

The experimental and actual data of torque according to the actual speed are shown in Fig. 13, and the tested equipment is included.

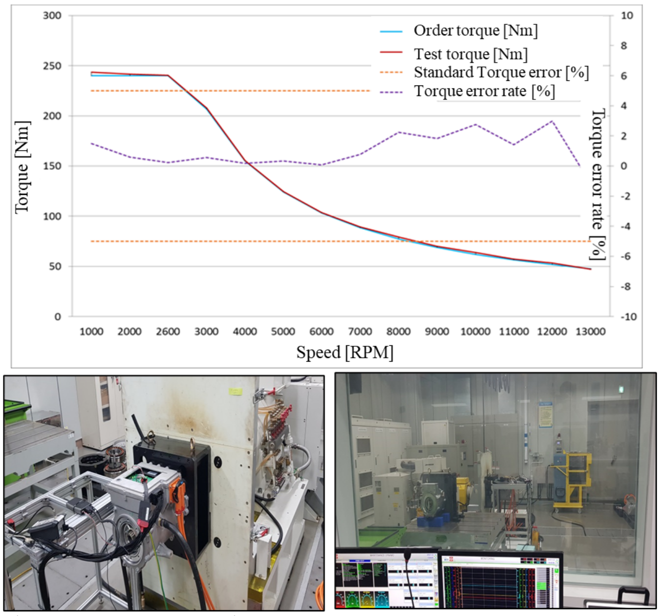

Fig. 13. Torque compensation.

As a result of the actual test, it was confirmed that the control method compensated for the electromagnetic field analysis was well suited.

V. Conclusion

Through the data of electromagnetic field analysis, the advantage of saving time compared to the existing current torque control was confirmed. The existing control method is to control the torque by creating a speed-torque current table. However, for this, a table for each voltage must be additionally prepared. It has the disadvantage that many additional tests are required to write it. However, if the flux-torque current table is prepared by compensating for the electromagnetic field simulation analysis value proposed in this paper, a five-point test is performed. Therefore, it shortens the existing test time and writes data through interpolate into a table, which reduces the current table creation time and enables accurate control.

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