# Inductance tracking Method for Interior Permanent Magnet Synchronous Motor by Electric Torque Estimator

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## Background

This letter proposed a new real-time inductances tracking algorithm. This algorithm estimates the inductance of interior permanent magnet synchronous motors (IPMSM) using electrical and mechanical equations. Unlike the convenience algorithms, the proposed online inductances identification algorithm does not need information on magnetic flux. Therefore, it can estimate parameters regardless of the change according to operation point and cross-saturation effect. In this paper, a new real-time parameter tracking algorithm is derived from electric torque estimator. The validity and usefulness of the proposed inductance estimation technique are verified by simulation and experimental results.

## Conclusion

❖ In this letter, this newly developed method for estimating the Ld and Lq from electrical and mechanical equation was proposed. The proposed parameter estimation method is derived from electrical torque estimator. The method can be easily implemented through the dq-axis voltage and current. Further, it is not affected by the non-linearity of magnetic flux, and thus accuracy has been enhanced. The usefulness and effectiveness of the algorithm is confirmed by MATLAB/Simulink, and the validity of the parameter estimation method is verified by the test motor.

## Introduction

❖ The estimation techniques can be divided into an offline parameter estimation techniques estimated through test operation and an online parameter estimation techniques estimated during operation. The offline parameter estimation techniques can be classified into the estimation methods which do the estimation at standstill conditions and ones implemented at operating conditions. The offline estimation methods in the standstill conditions include the DC current decay test and AC standstill methods. On the other hand, the estimation techniques for the operating conditions include the vector-controlled method and generator test . The advantage of the offline parameter estimation techniques is that it is easy to implement with a simple algorithm. Nevertheless, there is a disadvantage that additional equipment is required and measurement errors are caused by measurements performed at a single point.

❖ The online parameter estimation techniques are introduced as the model reference adaptive control techniques, observer-based techniques, extended kalman filter based Techniques, and neural network techniques. These techniques are suitable for applications that have various operation ranges, because it is estimated during operation. However, its algorithm is fairly complex, difficult to implement, and requires high-performance DSP.

❖ Previous technologies have the disadvantage that it does not take into account the irregular operating conditions of the motor or requires complex calculations. Additionally, the magnetic flux is required for the conventional parameter estimation techniques, which can vary due to the motor temperature or magnetic saturation. Thus, it is difficult to exactly estimate a parameter.

❖ This Letter proposes a new method with online parameters identification using electric torque estimator without considering the magnetic flux. This estimator is made up of dq axis voltage and current parameter so that the torque of the IPMSM can be calculated without additional equipment.

## Experiment

V. EXPERIMENTAL RESULTS

The proposed algorithm is constructed as shown in Fig. 2. It was tested at the base rate of 2,000 [rpm] of IPMSM and Ia = 6[A], beta = 7° for MTPA operation. Fig. 3 shows the experimental results. Fig. 3(a) shows the torque estimated using the dynamometer and the estimated torque using the torque estimator. The estimated torque was calculated by (5). Fig. 3(b) and (c) show the d and q-axis inductances, respectively, confirming that the actual values are well followed.

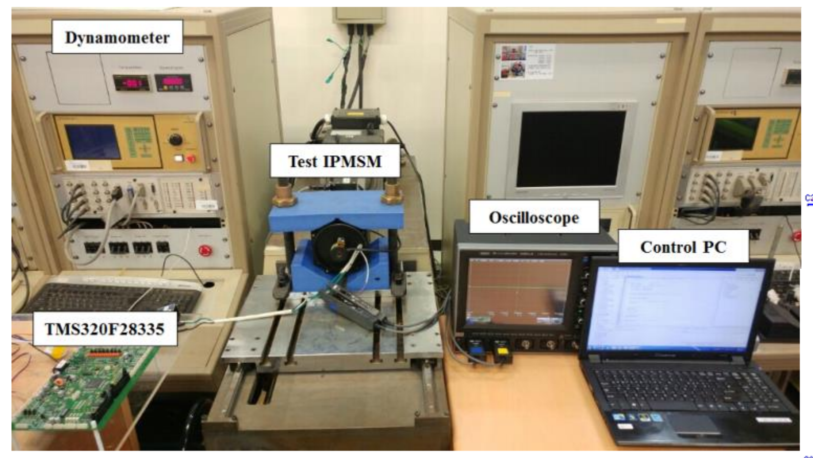
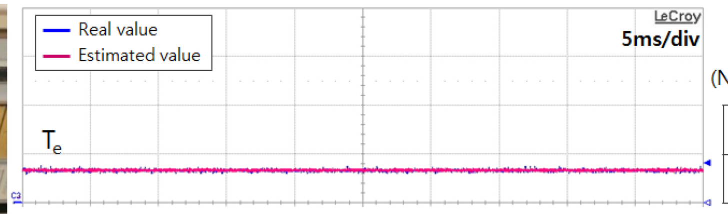
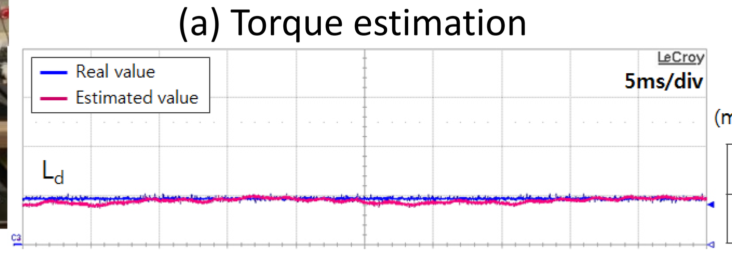


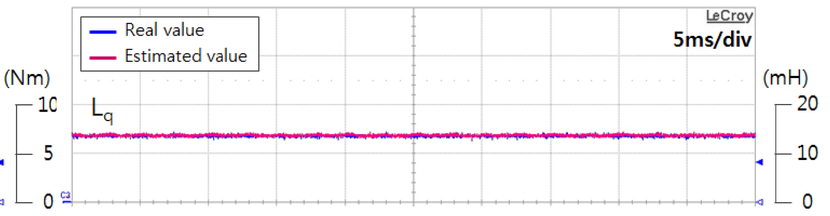

Fig. 2. Experimental Environment




(a) Torque estimation




(b) d-axis inductance estimation




(c) q-axis inductance estimation

Fig. 3. Experimental Results

## Design Process

II. ELECTRIC TORQUE ESTIMATOR

This paper proposes a method to estimate the torque using the output equation of IPMSM. The output equation of IPMSM is as follows.

$$P_{in} = \frac{3}{2}\left\{R_a\left(i_d^2 + i_q^2\right) + p\left(L_d i_d + L_q i_q\right) + \omega_r\left(\Phi_a i_q + L_d i_d i_q - L_q i_d i_q\right)\right\} \quad (1)$$

where, Pin is the input power, vd and vq are the dq-axis stator voltage, id and iq are the dq-axis stator current, Ra is the stator resistance, Ld and Lq are the dq-axis stator inductance, ωe is electrical stator angular velocity, Φa is permanent magnet flux linkage, p is differential operator, respectively.

In (1), the first term represents the stator copper loss, the second term represents the magnetic field energy, and the third represents the mechanical output. In steady state, there is no variation of magnetic field energy. The output power is represented by

$$P_{out} = P_{in} - P_c - P_i - P_m \quad (2)$$

where, Pin is the output power, Pc is the copper loss, Pi is the iron loss and Pm is the mechanical loss. The iron loss consists of eddy current loss and hysteresis loss. This can be expressed as [follows

$$P_i = P_{eddy} + P_{hysteresis} = K_e f^2 B_{\max}^2 + K_h f B_{\max}^n \approx K_e' \omega_m^2 + K_h' \omega_m \quad (3)$$

where, Ke is eddy current loss constant, Kh is hysteresis loss constant, Bmax is maximum flux density, n is material dependent Steinmetz loss constant (1.6 to 2.0). The loss constants Ke and Kh is determined by iron loss curve of the steel lamination.

Total mechanical losses are the bearing and windage loss, which can be expressed by

$$P_m = P_{bearing} + P_{windage} = 0.5\omega_m k_b F D_b + 0.03125\omega_m^3 \pi k_{ct} k_r \rho_{air} D_r^4 l_r \quad (4)$$

where, ωm is mechanical speed of the rotor, kb is bearing loss constant, F is force acting on the bearing, Db is bearing inner diameter, kct is torque codfficient, kr is roughness coefficient, ρair is density of air, Dr is rotor diameter, lr is rotor length. However, mechanical losses are negligible because the mechanical loss is very small compared to copper loss and iron loss.

Therefore, the output electrical torque can be represented by

$$T_e = \frac{P_{out}}{\omega_m} = \frac{3}{2\omega_m}\left\{\left(v_d i_d + v_q i_q\right) - R_a\left(i_d^2 + i_q^2\right)\right\} - \left(K_e'\omega_m + K_h'\right) \quad (5)$$

So, it is possible to estimate electric torque of IPMSM without additional test.

III. Online Parameter Tracking Methods

For vector control of IPMSM, the three-phase voltage equation formula of IPMSM was calculated through Clarke transformation and Park transformation in order, which obtained d-q axes voltage equation as

$$v_q = R_a i_q + \frac{dL_q i_q}{dt} + \omega_r L_d i_d + \omega_r \Phi_a \quad (6)$$

$$v_d = R_a i_d + \frac{dL_d i_d}{dt} - \omega_r L_q i_q \quad (7)$$

The torque equation of IPMSM is given as follows

$$T_e = \frac{3}{2}\frac{P}{2}\left\{\Phi_a i_q + \left(L_d - L_q\right) i_d i_q\right\} \quad (5)$$

This letter proposes the estimation of d- and q-axis inductances through electrical and mechanical equation without information on magnetic flux. Magnetic flux fluctuates due to temperature and saturation. Proposed estimation has more accurate values because it can estimate d and q axis inductance regardless of magnetic flux. The torque, d and q-axis currents at $t=t_1$ in (5) are $T_e(t_1)$, $i_d(t_1)$ and $i_q(t_1)$ respectively. At $t=t_2$, $T_e(t_2)$, $i_d(t_2)$ and $i_q(t_2)$ can be written as

$$\Delta T_e = T_e(t_2) - T_e(t_1)$$
$$= \frac{3}{2}\frac{P}{2}\left[\left\{\Phi_a i_q(t_2) + \left(L_d - L_q\right) i_d(t_2) i_q(t_2)\right\} - \left\{\Phi_a i_q(t_1) + \left(L_d - L_q\right) i_d(t_1) i_q(t_1)\right\}\right] \quad (8)$$

If the q-axis current is controlled to be constant during $t_1$~ $t_2$, the following expression can be obtained.

$$L_d - L_q = \frac{4\Delta T_e}{3P i_q \Delta i_d} \quad (9)$$

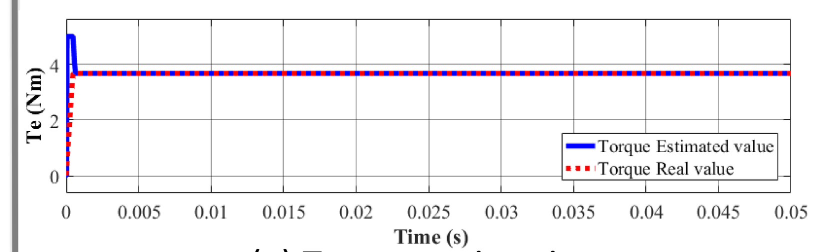
Q-axis inductance can be expressed as follows in the steady state by (6).

$$L_q = \frac{R_a i_d - v_d}{\omega_r i_q} \quad (10)$$

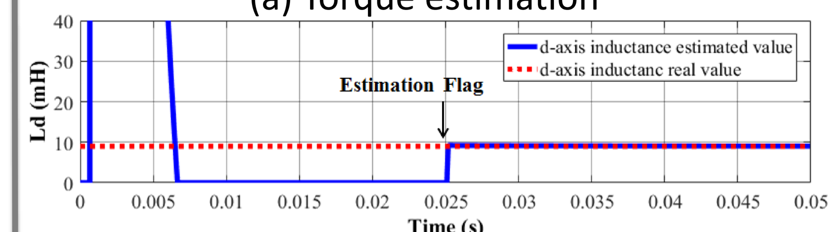
Therefore, $L_d$ and $L_q$ can be estimated by (9) and (10) by calculating $\Delta T_e$ in (8).

IV. Simulation Results

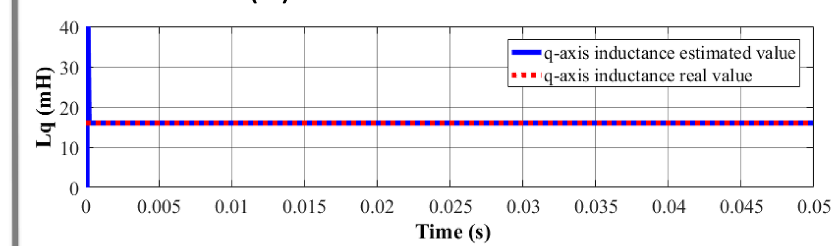
To verify the proposed inductance estimation method, it is simulated by MATLAB / Simulink. Specification details for the motor are in Table 1. D- and q-axis currents for maximum torque per ampere (MTPA) are operated and inductance estimation starts after 0.025sec. Fig. 1(a) shows the torque, and it can confirm that the estimated value agrees with the actual values after the transient state. Fig. 1(b) and (c) show the d- and q-axis inductances. Since the inductance estimation starts at 0.025sec, both d- and q-axis inductances follow the actual values well.




(a) Torque estimation




(b) d-axis inductance estimation




(c) q-axis inductance estimation

Fig. 1. Structure of MRAS scheme for inductance estimation.

TABLE I
THE SPECIFICATIONS OF IPMSM

| Description | Value | Unit |
|---|---|---|
| Pole | 4 | - |
| DC Link Voltage | 310 | V |
| Max. Current | 6 | A |
| Max. Torque | 3.6 | Nm |
| Phase Resistance | 0.511 | Ohm |
| d-axis Inductance | 9 | mH |
| q-axis Inductance | 13 | mH |
| Magnetic Flux | 0.2 | Wb |