Identification of PMSM Motor Parameters with a Power Analyzer

By Kunihisa Kubota, Hajime Yoda, Hiroki Kobayashi and Shinya Takiguchi

1 Introduction

Recent years have seen permanent magnet synchronous motors (PMSMs) and related control technologies rapidly permeate into the advanced power electronics landscape and markets. These developments reflect the advent of high-performance, high-efficiency designs thanks to progress in permanent magnet materials as well as the advantages of PMSMs relative to other motors in terms of quiet operation and simplicity of maintenance[1)]. Recently, PMSMs are being adopted in hybrid and electric vehicles in addition to household electronics and industrial machinery, and their entry into widespread use is expected to accelerate in the future[2)].

In general, PMSM analysis and control are based on the equivalent circuit model for a motor expressed on the *d*- and *q*-axes. A variety of high-performance control methods have been proposed for PMSMs, and these control algorithms are based on *d*-*q* equivalent circuits, making it extremely important to identify the equivalent circuit constants—in other words, the motor parameters (*d*-axis and *q*-axis inductance, L_d and L_q)—with a high degree of precision.

Of these motor parameters, L_q exhibits a particularly high degree of current dependence due to magnetic saturation[3, 4)], making it difficult to implement high-performance control while using low-precision motor parameters measured in a simple manner with an LCR meter or other instrument while the motor is in the stopped state.

This paper introduces a method by which a power analyzer can be used to identify motor parameters easily and with a high degree of precision while the target motor is operating. In addition, it provides results (motor parameters) obtained through the actual use of this method.

2 Method for identifying motor parameters

This chapter provides a brief description of the principles employed to identify PMSM motor parameters using a power analyzer and of a procedure for doing so.

2.1 Principles

If we assume the following with regard to the voltage equation for a PMSM expressed on the *d*-*q* coordinate axis, we arrive at Eq.(1)[3)].

i) The spatial distribution of magnetic flux in the gap between the stator and rotor takes the form of a sine wave moving along the gap.

ii) The harmonic components of the voltage and current can be ignored.

iii) Core loss can be ignored.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -\omega L_q \\ \omega L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \phi_a \end{bmatrix} \quad (1)$$

In this equation, v_d and v_q represent the *d*-axis and *q*-axis components of the armature voltage for each phase; i_d and i_q, the *d*-axis and *q*-axis components of the armature current for each phase; R, the armature resistance for each phase; p, the differential operator ($\mathrm{d}/\mathrm{d}t$); L_d and L_q, the *d*-axis and *q*-axis self-inductance; ω, the rotation angle (electrical angle) speed; and $\phi_a (= K_e)$, the RMS value of the permanent magnet's flux linkage with the armature (i.e., the induced voltage constant).

Fig. 1 illustrates the result of assuming a stationary state (so that time-derivative terms can be ignored) and expressing Eq.(1) as a *d*-axis and *q*-axis vector diagram.

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In the figure, v_1 and i_1 represent the fundamental components of the phase voltage and phase current, and θ_v and θ_i represent the fundamental phase angle of the phase voltage and phase current, respectively. Based on Fig. 1, the d-axis and q-axis voltage equations can be formulated as follows :

$$K_e\omega + Ri_q = v_q - \omega L_d i_d \tag{2}$$

$$v_d = Ri_d - \omega L_q i_q. \tag{3}$$

Solving these for L_d and L_q yields the following equations :

$$L_d = \frac{v_q - K_e\omega - Ri_q}{\omega i_d} \tag{4}$$

$$L_q = \frac{Ri_d - v_d}{\omega i_q}. \tag{5}$$

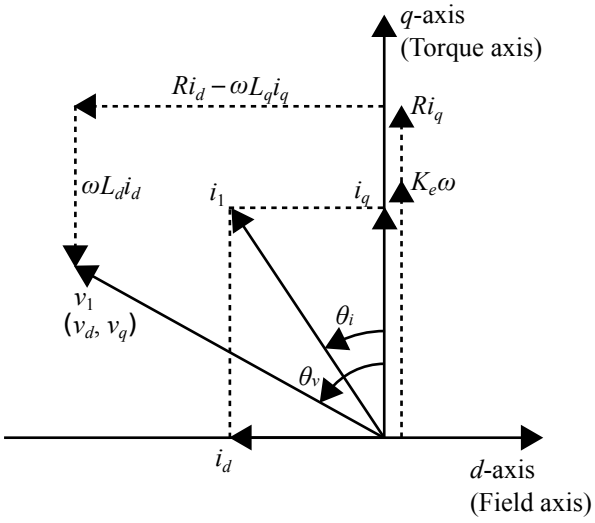

Fig. 1: PMSM vector diagram.

2.2 Identification procedure

This section describes a procedure by means of which a power analyzer can be used to identify motor parameters.

Although this specific procedure uses a Hioki Power Analyzer PW6001, motor parameters can be identified using a similar procedure with any power analyzer that provides an electrical angle measurement function that is equivalent to that offered by the PW6001.

2.2.1 Measuring the armature resistance R for each phase

Measure the armature resistance R for each phase using a resistance meter or other suitable instrument in advance.

2.2.2 Performing phase zero-adjustment and identifying the induced voltage constant K_e

After placing the motor terminals of the PMSM being measured in the open state ($i_d = i_q = 0$), connect the motor terminals to the "CH 1", "CH 2" and "CH 3" voltage inputs of the Power Analyzer PW6001. Additionally, connect the encoder's A-phase pulse output to "CH B", its B-phase pulse output to "CH C", and its Z-phase pulse (origin signal) output to "CH D" (Fig. 2).

Configure the Power Analyzer PW6001's settings by setting the motor analysis operating mode to "Single", the measurement parameter to "Torque Speed Direction Origin", and "CH B" input to "Pulse". In addition, set the wiring connection for "CH 1", "CH 2" and "CH 3" to "3P3W3M", the synchronization source to "Ext1", and Δ conversion to "ON". Setting the synchronization source to "Ext1" allows the voltage and current phase angles to be measured using the inputted encoder pulse as the reference, and setting Δ conversion to "ON" allows the line voltage to be converted to, and measured as, a phase voltage.

In this state, drive the motor from the load side to generate an induced voltage and perform phase zero-adjustment on the Power Analyzer PW6001. As a result of this step, θ_v and θ_i will represent the phase angle expressed using the phase of the induced voltage generated in the q-axis direction as the reference—that is, the electrical angle.

At this time, Eq.(4) can be rewritten as follows since the induced voltage v_q is equal to v_1, allowing identification of K_e.

$$K_e = \frac{v_q}{\omega} = \frac{v_1}{2\pi f_1} \tag{6}$$

In this equation, $f_1 (= \omega/2\pi)$ represents the frequency of the phase voltage's fundamental wave.

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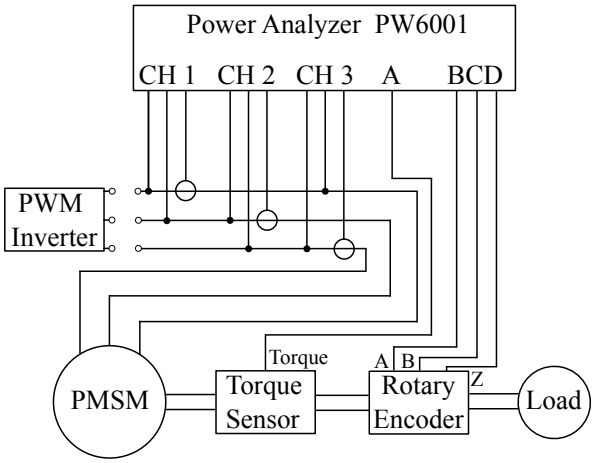

Fig. 2: Wiring connections when performing phase zero-adjustment and identifying the induced voltage constant K_e.

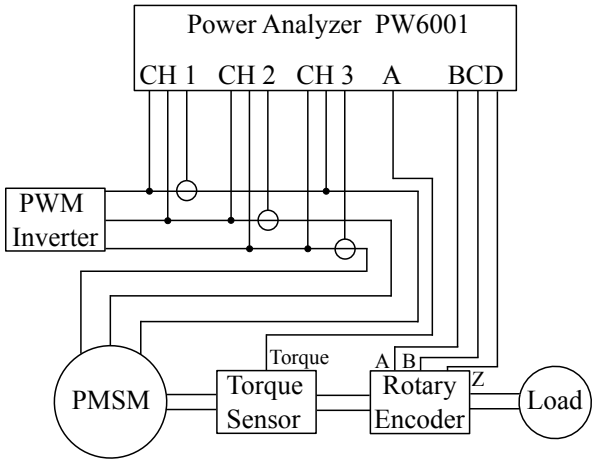

Fig. 3: Wiring connections when identifying the L_d and L_q motor parameters.

2.2.3 Identifying the motor parameters L_d and L_q with user-defined functions

The d-axis and q-axis self-inductance L_d and L_q can be identified using R as measured in Section 2.2.1 and K_e as identified in Section 2.2.2. First, connect the drive inverter output to the motor terminals that were left open in Section 2.2.2 and operate the motor (Fig. 3). At this time, the following equations will obtain based on Fig. 1:

$$v_d = -v_1 \sin\theta_v \tag{7}$$
$$v_q = v_1 \cos\theta_v \tag{8}$$
$$i_d = -i_1 \sin\theta_i \tag{9}$$
$$i_q = i_1 \cos\theta_i \tag{10}$$

By configuring the instrument's user-defined functions (UDFs) with these equations as well as Eqs.(4) and (5), it is a simple matter to identify L_d and L_q while monitoring v_d, v_q, i_d, and i_q. See reference[5] for specific examples of settings for the Power Analyzer PW6001's user-defined functions.

3 Measurement example

This section presents the results of using the procedure described in Section 2.2 to actually identify motor parameters.

3.1 Measurement conditions

Tables 1, 2 and 3 describe the specifications of the inverter (Fig. 1), drive-side motor, and load-side motor (Fig. 2) used in the procedure.
Table 4 describes the measuring instruments that were used. The Hioki Resistance Meter RM3544 noted in the table was used to measure the armature resistance R of the drive-side motor listed in Table 2 for each phase (Section 2.2.1).

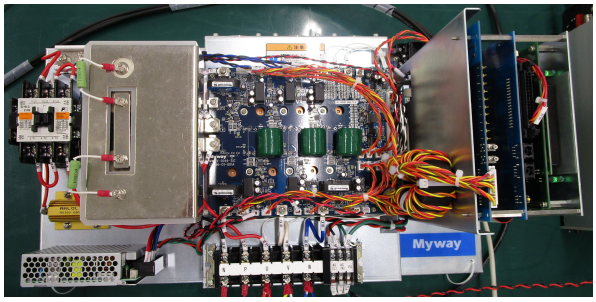

Fig. 1: Inverter.

3.2 Identifying the induced voltage constant K_e

The induced voltage constant K_e was identified using the procedure described in Section 2.2.2. For reference, Fig. 3 illustrates the induced voltage (phase voltage) waveforms for the drive-side motor and A/B/Z phase pulse waveforms for the encoder during the identifica-

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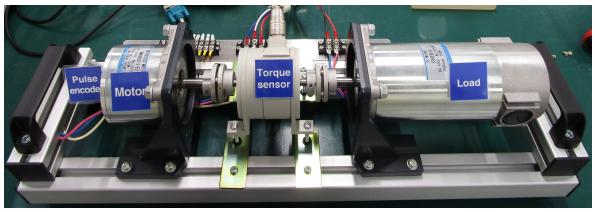

Fig. 2: Drive-side motor (left) and load-side motor (right).

Table 1: Inverter specifications.

Item	Specifications
Rated output capacity	10.0 kVA
Rated output voltage	AC 400 Vrms
Rated output current	AC 14.5 Arms
Rated input voltage	DC 700 V
Rated input current	DC 15.1 A
Maximum input current	DC 18.6 A
Input voltage range	From DC 0 V to DC 800 V
Switching frequency	Up to 200 kHz
Switching element	SiC MOSFET SCH2080KE (ROHM)
Manufacturer	Myway Plus Corp.

Table 2: Drive-side motor specifications.

Item	Specifications
Model	RM86A20-2-E8 DC brushless motor with encoder
Rated voltage	DC 100 V
Rated current	2 A
Rated rpm	2500 rpm
Rated output	120 W
Armature resistance for each phase	0.89768 Ω
Number of poles	8
Number of pulse per rotation	1024

Table 3: Load-side motor specifications.

Item	Specifications
Model	DC motor SS60E80-6
Rated voltage	DC 100V
Rated current	4.8 A
Rated rpm	2500 rpm
Rated output	350 W

Table 4: Measuring instruments

Instrument	Model	Manufacturer
Power Analyzer	PW6001	HIOKI E.E. Corp.
Current Sensor	CT6841	HIOKI E.E. Corp.
Resistance Meter	RM3544	HIOKI E.E. Corp.

tion process.

Fig. 4 illustrates the relationships between the motor rpm n, the RMS value v_1 of the fundamental component of the drive-side motor induced (phase) voltage, and the identified induced voltage constant K_e. The measured v_1 value varies proportionally with n, while the identified K_e value remains roughly constant, without regard to n. In this way, the relationships between these three values can be seen to satisfy the relationships described in Eq.(6).

K_e exhibits a small amount of variability during low-speed operation due to the more pronounced rotating unbalance of the motor in that operating regime.

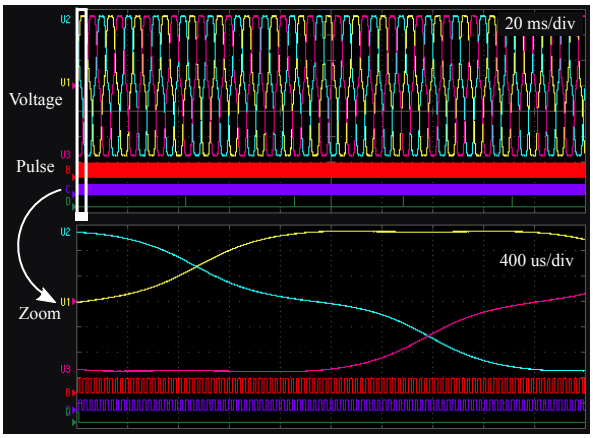

Fig. 3: Drive-side motor induced (phase) voltage and encoder's A/B/Z phase pulse waveforms during identification of the induced voltage constant K_e.

3.3 Identifying the L_d and L_q motor parameters

The d-axis and q-axis self-inductance L_d and L_q were identified using the procedure described in Section 2.2.3. For reference, Fig. 5 illustrates the inverter's secondary-side phase voltage and phase current as well as the encoder's A/B/Z phase pulse waveforms during identification.

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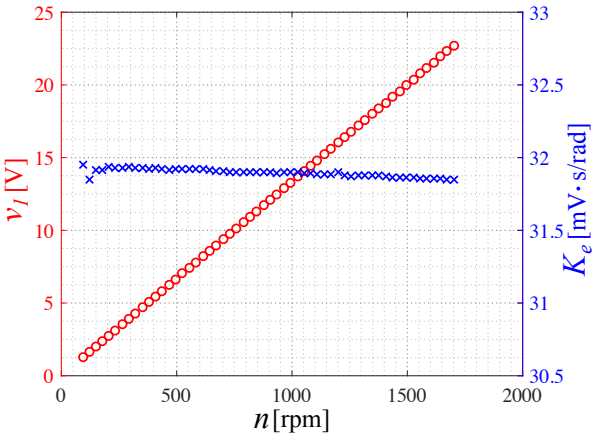

Fig. 4: Relationships between the motor rpm n, the RMS value v_1 of the fundamental component of the drive-side motor induced (phase) voltage, and the identified induced voltage constant K_e

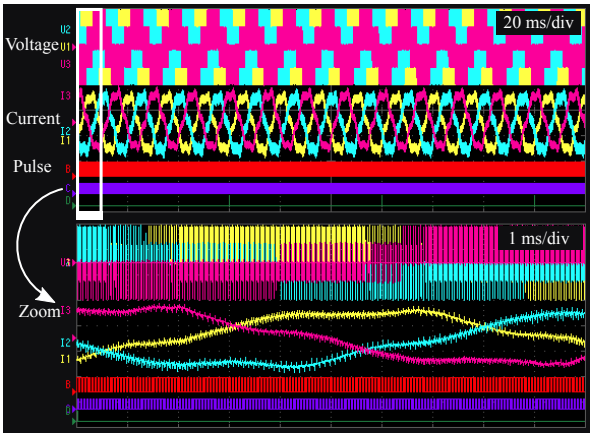

Fig. 5: Inverter secondary-side phase voltage and phase current and encoder's A/B/Z phase pulse waveforms during identification of the L_d and L_q motor parameters (when driving the motor with the inverter)

Fig. 6 illustrates the relationships between (a) the d-axis current i_d and the identified d-axis self-inductance L_d and (b) the q-axis current i_q and the identified q-axis self-inductance L_q. L_d remains roughly constant, without regard to i_d. By contrast, L_q exhibits a high degree of current dependency due to magnetic saturation and varies significantly with i_q. These characteristics make it clear that it is not possible to use an LCR meter or similar instrument to identify L_d with a high degree of precision while the motor is in the stopped state. Instead, the value must be identified while the motor is operating.

The variability in the L_d and L_q values when the i_d and i_q values are small is also likely to be caused by rotating unbalance of the motor during low-speed operation.

Fig. 6 illustrates the results of identifying the L_d and L_q motor parameters while the motor's rpm is varied while holding the current phase angle constant, showing the current dependence of L_d and L_q. The current phase angle dependence of the motor parameters can also be verified by applying this identification method.

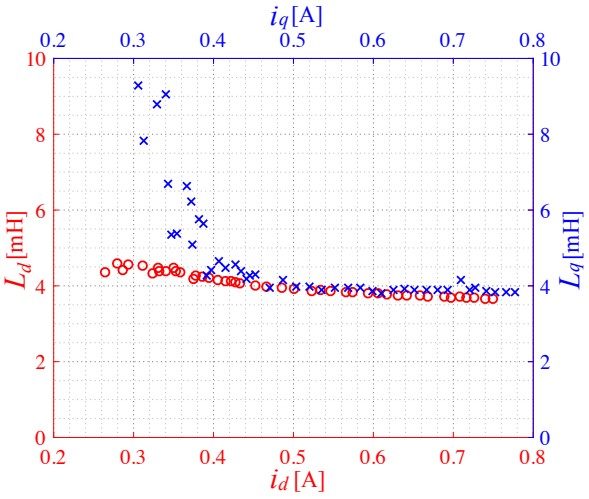

Fig. 6: Relationships between (a) the d-axis current i_d and the identified d-axis self-inductance L_d (shown in red) and (b) the q-axis current i_q and the identified q-axis self-inductance L_q (shown in blue).

4 Conclusion

This paper has introduced a method for identifying PMSM motor parameters easily and with a high degree of precision using a power analyzer. It also presents the results of using the introduced method along with a

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Hioki Power Analyzer PW6001 to identify actual motor parameters. It must be noted that the method introduced in this paper presumes the use of an analytical model that posits that core loss can be ignored. That said, by measuring mechanical loss and identifying the equivalent core loss resistance in advance, it would be possible to further develop the described method in order to identify motor parameters while taking into account core loss.

The identification of PMSM motor parameters introduced in this paper is only one example of an application for power analyzers, which can be used effectively in numerous other settings in the power electronics field. The authors look forward in the future to actively introducing other applications in which power analyzers can be effectively.

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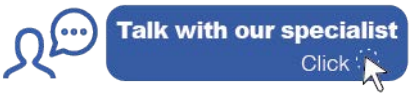

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