Parameter Identification of a Synchronous Reluctance Motor by using a Synchronous PI Current Regulator at a Standstill

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Abstract

This paper proposes an estimation algorithm for the electrical parameters of synchronous reluctance motors (SynRMs) by using a synchronous PI current regulator at standstill. In reality, the electrical parameters are only measured or estimated in limited conditions without fully considering the effects of the switching devices, connecting wires, and magnetic saturation. As a result, the acquired electrical parameters are different from the real parameters of the motor drive system. In this paper, the effects of switching devices, connecting wires, and the magnetic saturation are considered by simultaneously using the short pulse and closed loop equations of resistance and synchronous inductances. Therefore, the proposed algorithm can be easily and safely implemented with a reduced measuring time. In addition, it does not need any external or additional measurement equipment, information on the motor's dimensions, and material characteristics as in the case of FEM. Several experimental results verify the effectiveness of the proposed algorithm.

Key Words: Closed loop equations, Electrical parameter estimation, Short pulse, Synchronous PI current regulator, Synchronous reluctance motor

I. INTRODUCTION

Recently, synchronous reluctance motors (SynRMs) have received a lot of attention because of their high output power, low cost, and endurance in various industry applications. The saliency rotor has no magnets or windings, so it is mechanically robust for high speed operation and it is suitable for sensorless control [1]–[4]. The phase resistance and synchronous inductances are the basic parameters describing SynRM behavior. The researchers in [5] showed that the electrical angle of a current vector with respect to the high permeance axis (d -axis) is a function of the ratio of the d - and q -axis inductances for some control methods. The performance of the drive system depends on the PI gains of the synchronous PI current regulator and they are calculated from the electrical parameters [6]. Therefore, an exact measurement of the synchronous inductances is very important to the performance of the motor drive system.

For SynRMs, there is a nonlinear relationship between the stator inductances and the currents due to magnetic saturation in the d - and q -axes, respectively. This causes some problems

for accurate control of the SynRM [7]–[9]. It is not easy to measure the exact inductance parameters of a SynRM while considering the saturation effect. Several methods that measure or calculate the electrical parameters of a motor have already been proposed in [10], [11]. These methods simply measure the phase inductances but they need an external circuit. Moreover, they need to know the position information [10] or have to calculate a complex flux polynomial to obtain the synchronous inductances [11]. The researchers in [12] measured the SynRM synchronous inductances considering the iron loss from a single phase test. The phase current, voltage, active power, position information, and dc stator resistance are necessary for the synchronous inductance identification. In recent years, the Finite Element Method (FEM) has been applied to simulate the parameters under ideal conditions [13]. However, FEM requires the motor dimensions and the material characteristics to calculate the electrical parameters. To consider the parameters in a real situation, the inductances were calculated recursively from the measured voltages and currents, their previous values and the constant stator resistance [14]. The very important role of electrical parameters for sensorless control was considered in [15]. By using the recursive least-square method, the authors directly identified the electrical parameters in the sensorless control of a SynRM. This method estimated the electrical parameters by using the

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Fig. 1. Measurement diagram of stator inductances using an LCR meter.

measured voltages and currents, the identified matrices and their previous values. These conventional methods, in brief, are very complex to implement or can only be used under constrained conditions.

A synchronous PI current regulator is widely used for ac machine drives due to its capability in regulating ac signals over a wide frequency range [16], [17]. Electrical parameters are used to calculate the PI gains of a synchronous PI current regulator. As a result, the drive performance can be guaranteed by using the exactly measured electrical parameters.

This paper proposes a new method that uses a synchronous PI current regulator to measure the exact electrical parameters of the SynRM at a standstill, taking into full consideration the effects of both the switching devices and the connecting wire resistance. The influences of the parameters on the drive performance are also verified through several experimental results.

II. TWO CONVENTIONAL METHODS

A. Using an LCR meter

In general, the three phase inductances of a SynRM are given by [18]:

$$L(\theta) = \begin{bmatrix} L_s & L_{ms} & L_{ms} \\ L_{ms} & L_s & L_{ms} \\ L_{ms} & L_{ms} & L_s \end{bmatrix} + L_m \begin{bmatrix} \cos(2N\theta) & \cos(2N\theta - \frac{2\pi}{3}) & \cos(2N\theta + \frac{2\pi}{3}) \\ \cos(2N\theta - \frac{2\pi}{3}) & \cos(2N\theta + \frac{2\pi}{3}) & \cos(2N\theta) \\ \cos(2N\theta + \frac{2\pi}{3}) & \cos(2N\theta) & \cos(2N\theta - \frac{2\pi}{3}) \end{bmatrix} \quad (1)$$

where, L_s is the average stator self-inductance, L_{ms} is the stator mutual inductance, L_m is one of the stator inductances due to the rotor saliency, and N is the number of pole pairs.

In a synchronous reference frame, the d - and q - axis synchronous inductances of the SynRM stator can be acquired by using the Park transformation.

$$L_d = L_s - L_{ms} + 1.5L_m \quad (2)$$

$$L_q = L_s - L_{ms} - 1.5L_m. \quad (3)$$

Fig. 1 shows a measurement diagram of the two phase inductances using an LCR meter.

The inductance expression between the two phases, L_{AB} can be expressed as:

$$L_{AB} = 2L_s - 2L_{ms} - 3L_m \cos(2N\theta - \frac{2\pi}{3}). \quad (4)$$

Fig. 2. Inductance as a function of rotor position.

Applying (4) to (2) and (3), the d - and q -axis inductances of the SynRM can be derived in (5) and (6), respectively.

$$L_d = \frac{L_{AB \max}}{2} \quad (5)$$

$$L_q = \frac{L_{AB \min}}{2}. \quad (6)$$

The LCR meter can measure the line to line resistances at the actual rotor terminals. The phase resistance R_s can be easily obtained by:

$$R_s = \frac{R_{AB, avg}}{2} \quad (7)$$

where, $R_{AB, avg}$ is the average resistance value between the A- and B-phases.

$L_{AB \max}$ and $L_{AB \min}$ are the maximum and minimum inductances between the A- and B- terminals according to the rotor position as shown in Fig. 2.

B. Using the ac voltage and current source

The principle of measurement using the ac voltage and current (called the VI method in this paper) is similar to that of the LCR meter shown in Figs. 1 and 2. The power system supplies a sine voltage to the A- and B- terminals. The inductance between the two phases can be calculated as:

$$L_{AB} = \frac{1}{\omega} \sqrt{\left(\frac{V}{I}\right)^2 - 4R_s^2} \quad (8)$$

where, ω is the frequency of the applied sine voltage, I is the rms current that flows through the A-phase and the B-phase, V is the voltage between the two phases, and R_s is the measured phase resistance from the prior dc test.

In the VI method, the stator current and voltage can be measured by slowly rotating the rotor mechanically from 0 to 2π in one direction. The change in the line to line inductances that occurs as the rotor is rotated is depicted in Fig. 2. The resultant synchronous inductances L_d and L_q can be calculated by using (5), (6), and (8).

This method has some disadvantages in obtaining the profile of the inductances. Firstly, it takes a lot of time to measure the inductances. Secondly, it requires additional equipment such as voltage/current meters, and an ac power supply. Thirdly, using dc resistance in an inductance equation (8) causes measurement errors in calculating the synchronous inductance due to the error of the constant dc resistance. Finally, in order to get a wide range of values of the inductances, measurements using a greater than nominal current ($I_{rms} > I_{nom}$) could heat and damage the SynRM because of the long term exposure to high temperature.

Fig. 3. Conceptual diagram for resistance measurement.

III. PROPOSED ONLINE MEASUREMENT METHOD

The conventional methods can only measure the electrical parameters of the motor. In order to consider the effects of the switching devices as well as the connecting wires, the real inverter system must be analyzed and used to measure the electrical parameters.

A. Relationship between current deviation and electrical parameters

The d - and q -axis output voltages of a synchronous PI current regulator can be written at a standstill ($\omega_e=0$) in the Laplace Transform Domain (LTD) as in (9) and (10).

$$V_d^{r*}(s) = \frac{1}{s} [I_d^{r*}(s) - I_d^r(s)] [K_{id_cc} + sK_{pd_cc}] \quad (9)$$

$$V_q^{r*}(s) = \frac{1}{s} [I_q^{r*}(s) - I_q^r(s)] [K_{iq_cc} + sK_{pq_cc}] \quad (10)$$

where, $K_{id_cc} = R_d^* \omega_{cc}$, $K_{iq_cc} = R_q^* \omega_{cc}$, $K_{pd_cc} = L_d^* \omega_{cc}$, and $K_{pq_cc} = L_q^* \omega_{cc}$ are the PI gains of the synchronous PI current regulator. R_d^* & R_q^* , and L_d^* & L_q^* are the known d - and q -axis resistances and inductances respectively, ω_{cc} is the current regulator's bandwidth, which is directly related to the sampling time of the synchronous PI current regulator and the switching frequency [6]. $V_d^{r*}(s)$ and $V_q^{r*}(s)$ are the outputs of the synchronous PI current regulator, while $I_d^{r*}(s)$ and $I_q^{r*}(s)$ are the d - and q -axis reference currents calculated from the output of the speed controller. The terms, $I_d^r(s)$ and $I_q^r(s)$, are the real d - and q -axis currents measured from the motor terminals.

The mathematical model of a SynRM is given by:

$$\begin{cases} v_d^r(t) = R_s i_d^r(t) + L_d \frac{di_d^r(t)}{dt} - \omega_e L_q i_q^r(t) \\ v_q^r(t) = R_s i_q^r(t) + L_q \frac{di_q^r(t)}{dt} + \omega_e L_d i_d^r(t) \end{cases} \quad (11)$$

where, $v_d^r(t)$ and $v_q^r(t)$ are the d - and q -axis terminal voltages in the synchronous reference frame.

The LTD equation of (11) at standstill can be derived as:

$$\begin{cases} V_d^r(s) = (R_s + sL_d) I_d^r(s) \\ V_q^r(s) = (R_s + sL_q) I_q^r(s) \end{cases} \quad (12)$$

Fig. 3 shows a control block diagram of the SynRM drive system without a speed controller. The relationship between the reference voltages and the terminal voltages is as follows:

$$\begin{cases} V_d^{r*}(s) = V_d^r(s) + [R_{dL} + R_{dsw}] I_d^r(s) \\ V_q^{r*}(s) = V_q^r(s) + [R_{qL} + R_{qsw}] I_q^r(s) \end{cases} \quad (13)$$

where, R_{dL} and R_{qL} are the d - and q -axis connecting wire resistances. R_{dsw} and R_{qsw} represent the nonlinear effects of the switching devices.

From (12) and (13), the current deviation between the real and the reference currents can be derived as:

$$I_d^{r*}(s) - I_d^r(s) = \frac{sL_d + R_d}{K_{id_cc} + sK_{pd_cc}} sI_d^r(s) \quad (14)$$

$$I_q^{r*}(s) - I_q^r(s) = \frac{sL_q + R_q}{K_{iq_cc} + sK_{pq_cc}} sI_q^r(s) \quad (15)$$

where, $R_d = R_s + R_{dL} + R_{dsw}$ and $R_q = R_s + R_{qL} + R_{qsw}$ are the real d - and q -axis resistances, respectively.

B. Measurement of resistances at a standstill

In this section, a method of determining the resistance by using a synchronous PI current regulator is proposed by using the above analysis. If K_{id_cc} is zero, the transfer function of the d -axis current is easily derived as in (16) from (14).

$$\frac{I_d^{r*}(s)}{I_d^r(s)} = \frac{K_{pd_cc}}{sL_d + R_d + K_{pd_cc}} \quad (16)$$

When a step function of the d -axis current reference is applied, the transient state equation of the d -axis current can be derived as:

$$i_d^r(t) = \frac{i_d^{r*}(t) K_{pd_cc}}{R_d + K_{pd_cc}} \left(1 - e^{-\frac{R_d + K_{pd_cc}}{L_d} t} \right) \quad (17)$$

Because $L_d \ll R_d + K_{pd_cc}$, the d -axis current at the steady state can be approximately obtained as:

$$i_d^r(t) = \frac{K_{pd_cc}}{R_d + K_{pd_cc}} i_d^{r*}(t) \quad (18)$$

From (18), the d -axis resistance is calculated like (19).

$$R_d = \frac{i_d^{r*}(t)}{i_d^r(t)} K_{pd_cc} - K_{pd_cc} \quad (19)$$

Fig. 4. Principle of inductance measurement at a current.

The real current is smaller than the reference current in (18), so the measured resistance is always larger than zero (19).

The q -axis resistance is also given by:

$$R_q = \frac{i_q^*(t)}{i_q^r(t)} K_{pq-cc} - K_{pq-cc}. \quad (20)$$

When the information about the real current, the reference current and the arbitrary proportional gain is known from the drive system, the real d - and q -axis resistances can be easily calculated by using (19), and (20) as shown in Fig. 3.

C. Measurement of the stator inductances

The fact that the PI gains of the synchronous PI current regulator affect the current responses of the drive system was already proven in [6]. The gains can be calculated from the known resistances and inductances as mentioned above. If the PI gains are obtained by using the exact electrical parameters, the real current tracks the reference current quite well. This means that the control performance of the current regulator depends on the electrical parameters.

The system resistances that include the effects of the switching devices and the connecting wires are already known from the previous step, that is, $R_d = R_d^*$ and $R_q = R_q^*$. (14) can be rearranged to get a current transfer function as in (21).

$$\frac{I_d^r(s)}{I_d^*(s)} = \frac{\omega_{cc}(R_d + sL_q^*)}{L_d s^2 + (\omega_{cc}L_d^* + R_d)s + R_d\omega_{cc}}. \quad (21)$$

When the step function of the reference current is applied to (21), the d -axis current can be derived as the equation of the transient state shown in (22).

$$i_d^r(t) = i_d^*(t) + k_1 e^{-\delta t} i_d^*(t) + k_2 e^{-\gamma t} i_d^*(t) \quad (22)$$

where:

$$k_1 = \frac{\omega_{cc}}{L_d} \frac{1}{(\gamma - \delta)} \left(L_d^* - \frac{R_d}{\delta} \right)$$

$$k_2 = \frac{\omega_{cc}}{L_d} \frac{1}{(\gamma - \delta)} \left(\frac{R_d}{\gamma} - L_d^* \right)$$

$$\delta = \frac{(\omega_{cc}L_d^* + R_d) - \sqrt{(\omega_{cc}L_d^* + R_d)^2 - 4L_d\omega_{cc}R_d}}{2L_d}$$

$$\gamma = \frac{(\omega_{cc}L_d^* + R_d) + \sqrt{(\omega_{cc}L_d^* + R_d)^2 - 4L_d\omega_{cc}R_d}}{2L_d}$$

The current response of (22) is analyzed as follows:

At $t = 0$:

$$i_d^r(t) = i_d^*(t) + i_d^*(t) \frac{\omega_{cc}}{L_d} \frac{1}{(\gamma - \delta)} \left(\frac{R_d}{\gamma} - \frac{R_d}{\delta} \right) = 0 \quad (23)$$

At $t = t_1$, just before the steady state, $e^{-\delta t} \gg e^{-\gamma t}$ ($\gamma \gg \delta$) is satisfied and the d -axis current is approximately obtained at t_1 as in (24):

$$i_d^r(t) \approx i_d^*(t) + k_1 e^{-\delta t} i_d^*(t) \quad (24)$$

The current response in (24) can be divided into three cases:

- Case (1): if $L_d > L_d^*$: $k_1 > 0$; $i_d^r(t) > i_d^*(t)$: underdamped.
- Case (2): if $L_d = L_d^*$: $k_1 = 0$; $i_d^r(t) = i_d^*(t)$: critically damped.
- Case (3): if $L_d < L_d^*$: $k_1 < 0$; $i_d^r(t) < i_d^*(t)$: underdamped.

At $t = +\infty$: $e^{-\delta t} = 0$, $e^{-\gamma t} = 0$: $i_d^r(t) = i_d^*(t)$, the current reaches the steady state.

The analysis of the q -axis current response is the same as the d -axis current analysis that was just presented.

It is known from the analysis of (24), that the real current can track the reference well if and only if the known inductances are equal to the real inductances. Therefore, only case (2) can be used to determine the real inductances.

Fig. 5. Experimental drive system for SynRM.

The method of measuring the inductances is shown in Fig. 4, and is based on the following three steps:

- First, the proportional gain is adjusted to a small enough value to produce an overshoot in the current response.
- Then, the proportional gain is increased step by step until the overshoot is eliminated. When there is no overshoot, the minimum proportional value is the accurate P gain.
- The real inductance equals the proportional gain divided by the bandwidth of the PI current regulator.

The same procedure is needed to measure the q -axis inductance. The resultant equations for the inductance values are given in (25) and (26), respectively.

$$L_d = L_d^* = K_{pd_cc} / \omega_{cc} \quad (25)$$

$$L_q = L_q^* = K_{pq_cc} / \omega_{cc}. \quad (26)$$

IV. EXPERIMENTAL RESULTS

Fig. 5 shows the control system of the SynRM that was used to verify the proposed method experimentally. This system consists of a DSP board with a TMS320VC33 and FPGA, a diode bridge rectifier, an inverter using an IPM (Intelligent Power Module), and a 3 HP SynRM with 4-poles. The sampling period of the current regulator is 100 μ s. The PWM switching frequency is 5 kHz.

A. Using the VI method

Two terminals of the SynRM were connected to the adjustable ac power supply as shown in Fig. 1. The phase resistance was determined by a prior dc test. The stator currents and voltages were measured by slowly rotating the rotor mechanically from 0 to 2π in one direction, and the inductances can be calculated by using (5), (6), and (8).

Fig. 6 shows the experimental results of the measured inductances by changing the current range from 1 to 10 A. In the real system, it is not easy to measure the exact electrical parameters of the SynRM by using the VI method due to the saturation effect of the stator inductance as shown in Fig. 6.

This effect adds an additional error to the stator inductance of the VI method.

Fig. 6. Experimental results of inductance measurement using VI method.

Fig. 7. Experimental results of dq -axis resistances.

B. Proposed method

1) *Measurement of resistances:* Fig. 7 shows the current responses of the d - and q -axis currents at 4 A and the calculated d - and q -axis resistances in the steady state by using (19) and (20), respectively. The P gain is chosen arbitrarily only to observe the waveform of the current response and to measure the d - and q -axis resistances including the effects of the inverter and the connecting wires.

The experimental results of the d - and q -axis resistances and the dc resistance R_{dc} of the VI method are shown in Fig. 8. The current level is easily varied by using the reference current of inverter system from 0 to 10 A with the short duration of the one pulse current as shown in Fig. 7. The resistance steadily decreases when the test current increases. This phenomenon mainly comes from the nonlinear characteristics of the switching devices. A small deviation between the d - and q -axis resistances results from the Park transformation.

In order to determine the exact integral gains (I-gains) of the synchronous PI current regulator, the d - and q -axis resistances must be used. Inaccurate integral gains can cause a deterioration of the system performance not only in the steady state but also in the transient state. The proposed method, that exactly measures the electrical parameters of the inverter fed SynRM including the effect of the switching devices and the connecting wires, guarantees improved drive performance of SynRMs.

2) *Measurement of the stator inductances:* Fig. 9 shows the waveforms of the dq -axis currents for three cases: underdamped, critically damped, and overdamped.

First, the proportional gain (K_{p_cc}) of the d -axis or the q -axis is set to a small value by using a small input inductance to produce an overshoot as shown in Figs. 9 (a) and (d), respectively. Then, K_{p_cc} is increased slowly to eliminate the overshoot.

Figs. 9 (b) and (e) show the critically damped current

Fig. 8. Experimental results of dq -axis and dc resistances by using the proposed and dc method.

responses with suitable gains and accurate parameters. The synchronous inductances are calculated directly by using the accurate proportional gains and the bandwidth as shown in (25) and (26), respectively.

Fig. 10 shows a comparison of the experimental results of inductances between the VI method and the proposed method. The q -axis inductance approaches the saturated region earlier than the d -axis inductance because of the rotor structure in the SynRM. As shown in Fig. 10, the proposed method is implemented by using the short duration of the step current to measure the electrical parameters. In addition, the measurement errors between the VI method and the proposed algorithm below 3[A] are generated by measurement noises in the regions of the low reference currents.

A better system response was obtained from the well tuned parameters and PI gains not only in the steady state but also in the transient state as shown in Fig. 11. The inductance deviation between the two methods is small as shown in Fig. 10. If the parameters of the VI method are used, the large deviation of stator resistance seen in Fig. 8 causes an overdamped response as shown in Fig. 11. Therefore, the proposed method was used to exactly measure the electrical parameters of SynRMs as shown in Figs. 7, 8, 9, 10, and 11.

C. Effect of motor parameters on system response

To evaluate the feasibility of the proposed method, the inverter fed SynRM is tested from standstill to 500 r/min without a load. The PI gains calculated from the parameters of the VI and proposed methods were turned to adapt to the operating currents. The experimental waveforms of the d - and q -axis currents are shown in Fig. 11 (a), (b), (c), and (d), (e), (f), respectively.

V. CONCLUSIONS

This paper proposes a new algorithm to measure the electrical parameters of a SynRM by using a synchronous PI current regulator at a standstill. The proposed algorithm can be easily and safely implemented by simultaneously using the short one-pulse and closed equations of resistance and synchronous inductances. Furthermore, the measurement time can be greatly reduced. In addition, the drive system itself is capable of measuring the electrical parameters, taking into full consideration the effects of the switching devices, connecting wires, and saturation by using the proposed method. It does not need any external or additional equipment for the

Fig. 9. Experimental results of dq -axis inductances measurement by using the proposed algorithm. (a) d -axis current underdamped. (b) d -axis current critically damped. (c) d -axis current overdamped. (d) q -axis current underdamped. (e) q -axis current critically damped. (f) q -axis current overdamped.

Fig. 10. Comparison results of synchronous dq -axis inductances between VI method and proposed method.

measurement. Moreover, this method can measure the exact electrical parameters without any information on the motor's dimension or material characteristics as in the case of FEM. The effectiveness of the proposed algorithm is verified through several experimental results.

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Fig. 11. Experimental results of speed and dq -axes current responses. (a), (b), and (c) VI method. (d), (e), and (f) proposed algorithm.

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