Electrical Parameter Tests of Synchronous Reluctance Motor

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Abstract

The electrical parameters are used to calculate gains in the current regulator as well as to determine the reference currents of speed controller in various control strategies of Synchronous Reluctance Motors (SynRMs). Many methods of measuring or estimating the electrical parameters of SynRM have been proposed by other authors. But almost papers only measure or estimate in the limited conditions without fully considering the effects of inverter, connecting wire and magnetic saturation. The parameter results are usually different from the real system parameters. The drive performance, therefore, can not be good if using inaccurate parameters.

In this paper, several methods used to measure the electrical parameters are introduced. The first method is LCR meter. And then, a method determining inductances by measuring AC current and voltage from AC power supply is presented. A new method with high reliability is proposed to measure the electrical parameters of SynRM.

The experiment results verify the effectiveness of the new proposed method.

1. Introduction

The synchronous reluctance motors (SynRMs) have gotten much attention in recent years because of their advantages in output power, cost and enduring ability. The phase resistance and synchronous inductances are the basic parameters describing the SynRM behavior. They are used to determine gains in the speed controller and the current regulator. Especially, the main control parameter of SynRM is the electrical angle of the current vector with respect to the high permeance axis (d-axis). The authors in [1] showed that this angle is the function of the synchronous inductance ratio. Therefore the exact measurement of the synchronous inductance is very important to establish the control drive.

The SynRMs have the non-linear relationship of inductances and currents due to the magnetic saturation effects in the d and q axes. So it is not easy to measure the exact inductance parameters in the SynRMs. Several methods measuring or estimating the electrical parameters have already been proposed in [2-3]. The conventional methods are very complex to be implemented or used in the constraint conditions. In addition, the effects of inverter and wire are not fully considered. These deteriorate the performance of motor drive system. This paper explains some very simple methods to measure the parameters in the different operating conditions and proposes a new method to measure exactly parameters combining with system analysis.

2. Principle of two simple measurement methods

2.1. Using LCR meter

The synchronous inductances of SynRM are written by:

$$L_d = L_s - L_{ms} + 1.5L_m\,;\; L_q = L_s - L_{ms} - 1.5L_m \tag{1}$$

Where, L_d is the direct axis inductance and L_q is the quadrature axis inductance. Here L_s is the average stator self-inductance, L_{ms} is the average stator mutual-inductance, L_m is the variation in stator inductance due to the rotor saliency.

The principal schematic for measurement of the two phase inductances using LCR is shown in Fig 1. The expression of inductance of two phases is shown in (2):

$$L_{AB} = 2L_s - 2M_s - 3L_m\cos(2N\theta - \frac{2\pi}{3}) \tag{2}$$

L_{ABmax} and L_{ABmin} are the maximum and minimum values of L_{AB} according to a mechanical revolution. Applying (2) to the equation (1) the d- and q- axes inductances of the SynRM are:

$$L_d = \frac{L_{AB\,max}}{2}\,;\;\; L_q = \frac{L_{AB\,min}}{2} \tag{3}$$

The LCR meter measures the two phase resistances, and one phase resistance is easily gotten:

$$R_s = \frac{R_{AB.avg}}{2} \tag{4}$$

Where, R_{AB} is the resistance between phase A and phase B, and $R_{AB.avg}$ is the average value of R_{AB}.

2.2. AC voltage and current measurement method

This method is similar to the LCR meter method. The power system supplies a sine voltage to the A, B phase windings as shown in Fig. 1. The two phase inductance is derived as (5).

$$L_{AB} = \frac{1}{\omega}\sqrt{\left(\frac{V_2}{I}\right)^2 - 4R_s^2} \tag{5}$$

Here ω is the frequency of the AC source, I – the RMS current flows through phase A and phase B, V_2 – the voltage between two phases. The synchronous inductances are also calculated by (3).

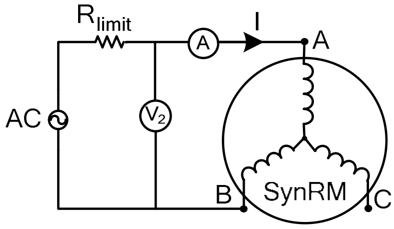

Fig. 1. The schematic diagram to measure the inductance

3. Online Tests for SynRM drive System

3.1. Relationship between current deviation and the drive system electrical parameters

The reference voltages of the synchronous PI current regulator of SynRM can be written like (6):

$$\begin{cases} v_d^{r*}(t) = K_{id\_cc}\int[i_d^{r*}(t) - i_d^r(t)]dt + [i_d^{r*}(t) - i_d^r(t)]K_{pd\_cc} - \omega_e L_q^* i_q^r(t) \\ v_q^{r*}(t) = K_{iq\_cc}\int[i_q^{r*}(t) - i_q^r(t)]dt + [i_q^{r*}(t) - i_q^r(t)]K_{pq\_cc} + \omega_e L_d^* i_d^r(t) \end{cases} \tag{6}$$

Where $K_{id\_cc} = R^*_d\omega_{cc}$, $K_{iq\_cc} = R^*_q\omega_{cc}$ and $K_{pd\_cc} = L^*_d\omega_{cc}$, $K_{pq\_cc} = L^*_q\omega_{cc}$; R^*_d, R^*_q and L^*_d, L^*_q are the reference resistances and inductances of current regulator in d- and q-axes respectively, ω_{cc} is the bandwidth of the current regulator. ω_e is the electrical angular velocity. The reference voltages $v_d^{r*}(t), v_q^{r*}(t)$ are generated by current regulator, and $i_d^{r*}(t), i_q^{r*}(t)$ are the output currents of speed controller. $i^r_d(t)$, $i^r_q(t)$ are the real d- and q-axes currents.

In addition, the electrical model of the SynRM in the *d–q* reference frame is given by

$$\begin{cases} v_d^r(t) = R_s i_d^r(t) + L_d \dfrac{di_d^r(t)}{dt} - \omega_e L_q i_q^r(t) \\ v_q^r(t) = R_s i_q^r(t) + L_q \dfrac{di_q^r(t)}{dt} + \omega_e L_d i_d^r(t) \end{cases} \tag{7}$$

The relationship between the reference voltages and the terminal voltages is written as follows:

$$\begin{cases} v_d^{r*}(t) = v_d^r(t) + \Delta V_d \\ v_q^{r*}(t) = v_q^r(t) + \Delta V_q \end{cases} \tag{8}$$

Here ΔV_d and ΔV_q represent the voltage errors due to the on – state voltage drop of switching device resistance and connecting wire resistance. In general, the voltage error can be written by

$$\begin{cases} \Delta V_d = (R_{dL} + R_{dsw}) i_d^r(t) \\ \Delta V_q = (R_{qL} + R_{qsw}) i_q^r(t) \end{cases} \tag{9}$$

Where R_{dL} and R_{qL} are the d- and q-axes wire resistances, the switching device resistances are R_{dsw}, R_{qsw}.

Laplace transform of equation (8) is

$$\begin{cases} V_d^{r*}(s) = V_d^r(s) + (R_{dL} + R_{dsw}) I_d^r(s) \\ V_q^{r*}(s) = V_q^r(s) + (R_{qL} + R_{qsw}) I_q^r(s) \end{cases} \tag{10}$$

From (6) and (10), the current deviation at standstill is derived:

$$I_d^{r*}(s) - I_d^r(s) = \frac{(sL_d + R_d)}{(R_d^* + sL_d^*)} \frac{sI_d^r(s)}{\omega_{cc}} \tag{11}$$

$$I_q^{r*}(s) - I_q^r(s) = \frac{(sL_q + R_q)}{(R_q^* + sL_q^*)} \frac{sI_q^r(s)}{\omega_{cc}} \tag{12}$$

With $R_d = R_s + R_{dL} + R_{dsw}$ and $R_q = R_s + R_{qL} + R_{qsw}$. R_d and R_q are the real d-q axis system drive resistances.

3.2. The measurement of the drive system resistances

From (11), assuming $R_d^* = 0$ ($K_{id\_cc} = 0$), transfer function of d-axis current is easily expressed as:

$$\frac{I_d^r(s)}{I_d^{r*}(s)} = \frac{\omega_{cc} L_d^*}{sL_d + R_d + \omega_{cc} L_d^*} = \frac{K_{pd\_cc}}{sL_d + R_d + K_{pd\_cc}} \tag{13}$$

The d-axis current response with a step function input current is:

$$i_d^r(t) = \frac{i_d^{r*}(t) K_{pd\_cc}}{R_d + K_{pd\_cc}} \left(1 - e^{-\frac{R_d + K_{pd\_cc}}{L_d} t} \right) \tag{14}$$

The d-axis current at steady state is as follows

$$i_d^r(t) = \frac{i_d^{r*}(t) K_{pd\_cc}}{R_d + K_{pd\_cc}} \tag{15}$$

The d and q axes drive system resistances are expressed

$$R_d = \frac{i_d^{r*}(t)}{i_d^r(t)} K_{pd\_cc} - K_{pd\_cc} \tag{16}$$

$$R_q = \frac{i_q^{r*}(t)}{i_q^r(t)} K_{pq\_cc} - K_{pq\_cc} \tag{17}$$

3.3. The estimation of the synchronous inductances

The gains in current regulator have the very large effects to current responses of the drive system. When the real current of the system well tracks to the reference current, the input resistances and inductances of current regulator are equal to the real resistances and inductances of motor.

With assuming the system resistances are already gotten exactly from the previous steps, it means $R_d = R^*_d$ and $R_q = R^*_q$. The equation (11) is rewritten as the transfer functions.

$$\frac{I_d^r(s)}{I_d^{r*}(s)} = \frac{\omega_{cc}(R_d + sL_q^*)}{L_d s^2 + (\omega_{cc} L_d^* + R_d)s + R_d \omega_{cc}} \tag{18}$$

The d-axis current response of the system is given by:

$$i_d^r(t) = i_d^{r*}(t) + k_1 e^{-\delta t} i_d^{r*}(t) + k_2 e^{-\gamma t} i_d^{r*}(t) \tag{19}$$

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

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

$$k_1 = \frac{\omega_{cc}}{L_d} \frac{1}{(\gamma - \delta)} \left(L_d^* - \frac{R_d}{\delta} \right); k_2 = \frac{\omega_{cc}}{L_d} \frac{1}{(\gamma - \delta)} \left(\frac{R_d}{\gamma} - L_d^* \right)$$

At t = t₁ is enough large for satisfying $e^{-\delta t} >> e^{-\gamma t}$ ($\gamma >> \delta$), the d-axis current response at t_1: $i_d^r(t) = i_d^{r*}(t) + k_1 e^{-\delta t} i_d^{r*}(t)$ (20)

Current response in (20) can be divided to three cases:

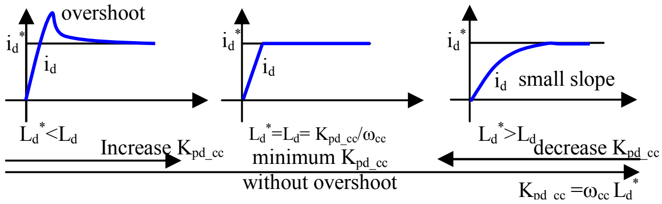

Fig. 2. Principle of the d - axis inductance test

4. Experimental results

To validate the above methods a SynRM 3 Hp, 220 V, 4 Poles is used. With the first method the motor is connected to a HIOKI 3532-50 LCR HiTESTER. The second method is performed by using a AC power system supplies to SynRM.

4.1. Using LCR meter

The motor inductance is measured by adjusting LCR meter parameters at 38 mA and 94 mA and frequency f=60 Hz. And Table 1 shows the results of the synchronous inductances. In addition, the LCR meter also displays directly the AB resistance. The average of the two phase resistance is $R_{AB.avg}$= 1.28 Ω . So the phase resistance is R_s= 0.64 Ω.

Table 1. The synchronous Inductances by using LCR meter

	$L_{AB.max}$(mH)	$L_{AB.min}$(mH)	L_d(mH)	L_q (mH)
I=38mA	31.522	23.192	15.766	11.596
I=94 mA	33.214	28.120	16.607	14.06

The LCR meter is a very simple method. However the LCR meter has a small voltage range, the inductance is only considered in a small range current (under 100 mA). This is the big disadvantage of measuring the electrical parameters by LCR meter.

4.2. AC voltage and current measurement method results.

The two phases of the SynRM are connected to the AC source f = 60 Hz. The oscilloscope is used to measure exactly the RMS voltages and currents of the SynRM.

The RMS current and voltage meters show the current I and voltage V_2 as Fig. 1. The two phase inductance is calculated from (3). The results of this method are in Fig. 7. The reliability of this method will be improved if the stator resistance R_s at the different current conditions is known exactly.

4.3. The proposed method tests

The proposed methods are verified by using the system including a DSP control board, a IPM, and a SynRM as Fig 3

4.3.1. The drive system resistance tests

Fig. 4 shows the block diagram of the proposed method for testing the d-axis and q-axis system resistances.

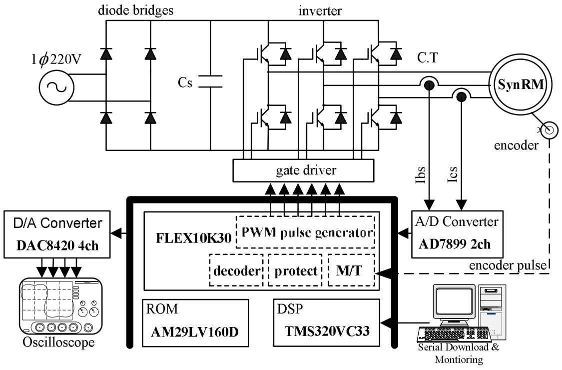

Fig. 3. The system for the SynRM system drive electrical parameter test

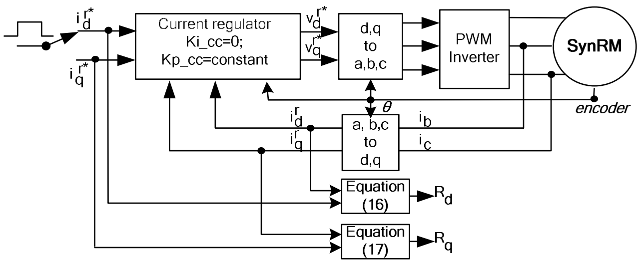

Fig. 4. Block diagram for testing the system drive resistances.

The current response of the d-axis current and the d-axis drive system resistance calculated from (16) when the reference current is 3 A and the proportional and integral gains are K_{pd_cc} = 20, K_{id_cc}= 0 as shown at the first waveform in Fig. 6. The proportional gain is chosen in such a way as to observe the waveform of the current response clearly. The results of the d- and q-axes drive system resistances are shown in Fig. 5. The system resistance decrease when the test current is increased is result in the effects of the inverter.

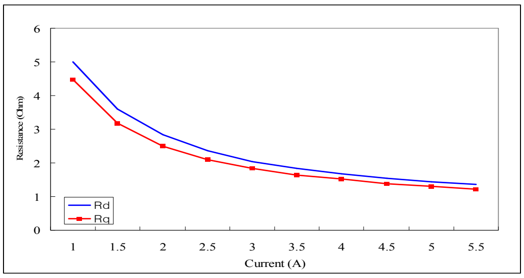

Fig. 5. The d- and q- axes resistances according to the current variation

4.3.2. The synchronous inductance tests

The last three waveforms of Fig. 6 show the waveform of current response of the d-axis current at three cases as explained in part 3.3 when the test current is 3A. Fig. 6. case 1 shows the overshoot because the input inductance of the current regulator in this case L^*_d=17 mH is smaller than real value L_d=20.8 mH. Fig.6.case 2 shows the current response at L^*_d=25 mH > L_d= 20.8 mH, it is clearly that the d-axis real current increase slowly to track to the reference current. Fig. 6.case 3 shows the suitable value of the d-axis inductance. Fig. 7 shows the comparison of the d-axis and q-axis inductances among the VI method, the new proposed method and FEM simulation. The results have the big deviation at small current because of the large effect of the inaccurate resistance at the small current test. In addition, the VI method only considers the effect of current flowing two coils and the value at each current is established from many tests. So the reliability of the VI method is not high.

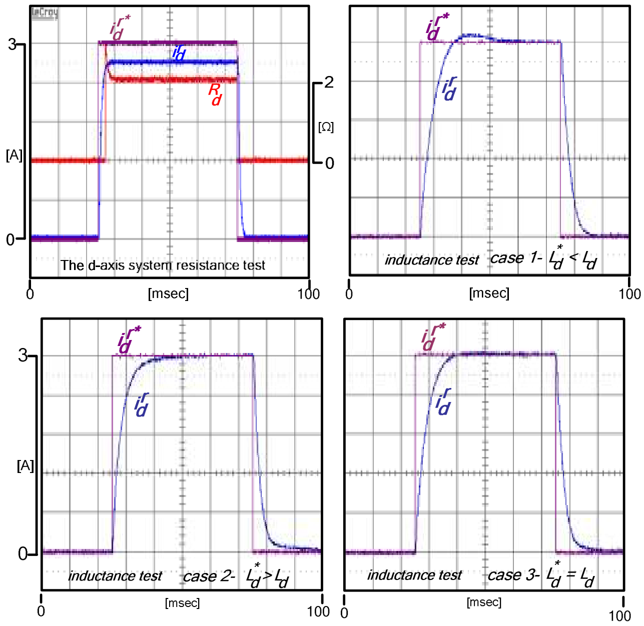

Fig. 6. The d-axis current response: resistance and inductance test

Because of the effect of saturation the inductances in the d- and q- axes directions decrease fast at small current and slowly at high current when the testing current is increased.

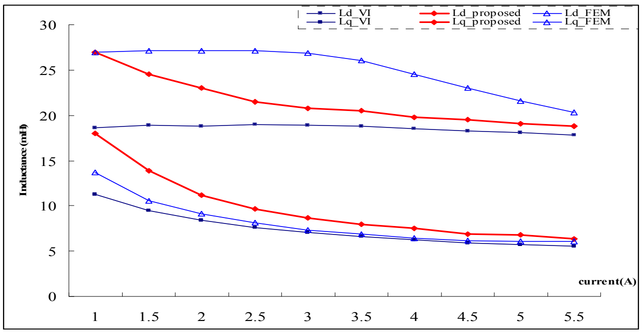

Fig.7. Comparison of the d-axis and q-axis inductance results

5. Conclusions

This paper introduces and explains the simple conventional methods for measuring synchronous inductances and resistances in the different measurement conditions by using LCR meter or measuring the AC currents and voltages. The new methods are proposed to test exactly the d-q axes resistances and inductances of the SynRM drive system. The experimental results verify the effectiveness of the new method. This work not only measures exactly the electrical parameters of SynRM but also verify the effect of the accurate gains in current regulator to the drive performance.

Acknowledgment

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Reference

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