PARAMETER MEASUREMENT FOR SYNCHRONOUS RELUCTANCE MOTORS CONSIDERING STATOR IRON LOSS IN STANDSTILL CONDITION

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ABSTRACT – Machine parameters need to measure in advance for vector control and theoretical analysis. Therefore, we present the machine parameter measurement scheme, considering stator iron loss, by the single-phase test at standstill condition. Using this method, the d-q axis inductances and the equivalent iron loss resistance in the voltage equation considering stator iron loss are easily measured. This method is simple and does not need to use complex theory and expensive equipment

1 . INTRODUCTION

Recent interest synchronous reluctance motors (Syn. RM) has increased in the context of possible applications in vector control, especially high speed operations[1]. Since the increase of driving frequency with high-speed operation leads the iron loss, consideration of iron loss is important issue. Therefore, the authors has proposed the modeling and vector control for Syn. RM considering stator iron loss[2]. The stator iron loss is modeled by additional windings on d-q axes, and the model is introduced as an assumption that the loss in the stator core is produced in equivalent eddy current windings on d-q axes[3]. The usefulness of the proposed model has been verified in computer simulations.

Vector control is now widely used for the speed and position control for Syn. RM drives in high performance applications. However, to achieve precise vector control and analysis for Syn. RM based on the model, which takes stator iron loss into account, machine parameters in the voltage equation need to measure in advance. As compared with synchronous motors with field windings, parameter measurement for Syn. RM and permanent magnet synchronous motors is difficult because no-load saturation curve and short-circuit curve cannot be obtained. Although we have proposed the single-phase test[4] and the $P-Q$ circle diagram method to parameter measurement[5], these methods were several problem. The single-phase test can measure the parameters in standstill condition, but this method cannot be applied to the Syn. RM without neutral point of stator winding. The $P-Q$ circle diagram method was tedious to execute actual load test in various load conditions. Moreover, saturation effect for d-q inductances cannot be observed.

In this paper, we present the machine parameter measurement scheme by the single phase test without neutral point of stator winding. Using this method, the d-q axis inductances and the equivalent iron loss resistance in the voltage equation considering stator iron loss are measured at standstill condition. In this method, the Syn. RM is brought into standstill condition, and the single-phase sinusoidal voltage is applied to the motor directly when the angular difference between a-phase winding axis and d axis is 90 ° and 0 ° respectively. Then, the phase voltage, phase current, and active power are measured, and the equivalent parameters, L_d, L_q, and r_m are calculated by using the measured values. Therefore, all the machine parameters in the voltage equation considering stator iron loss can be measured by the single-phase test.

Experimental results are illustrated to confirm the validity of the proposed method. We measured the d-q axis inductances and equivalent iron loss resistance characteristics in various currents and frequencies in experiment. Furthermore, the validity of the measured parameters is confirmed by using relationship between the active power and current. This method is simple and does not need to use complex theory and equations, because this measurement is achieved in standstill condition without any expensive equipment. In this proposed method, we can measure all the machine parameters in the voltage equation considering the stator iron loss for Syn. RM.

2. VOLTAGE EQUATION FOR SYN. RM CONSIDERING STATOR IRON LOSS

In the development of a voltage equation considering the stator iron loss, the following assumptions are made:

(a): Harmonic components of current and flux are neglected,

(b): There is no saturation in magnetic circuit, and the rotor iron loss and stray load loss are neglected,

(c): The stator iron loss is produced in the equivalent circuit for eddy current.

Because pulse-width modulation techniques have improved in recent years, a sinusoidal current or voltage can be supplied to the motor. Therefore, assumption (a) is valid in vector control for Syn. RM. Assumption (c) means that the eddy currents distributed on the stator core are dealt with as lumped electrical circuits.

By transforming three-phase winding axes into *d-q* axes, the *d-q* winding model that includes the equivalent eddy current windings on the stator is derived as Fig. 1, and the rotor has no damping windings. In this figure, 1*d* and 1*q* express the *d-q* stator windings, and 3*d* and 3*q* express the *d-q* equivalent eddy current windings, and the *d-q* axes are the rotating reference frame that rotates at rotor angular velocity. Using Fig. 1, the voltage equation taking into account of the stator iron loss for Syn. RM in the stationary reference frame and the rotor reference frame are given as (1) and (2), respectively,

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} r_1 + r_m & 0 \\ 0 & r_1 + r_m \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + p \begin{bmatrix} L_d \cos^2\theta + L_q \sin^2\theta & (L_d - L_q)\sin\theta\cos\theta \\ (L_d - L_q)\sin\theta\cos\theta & L_d \sin^2\theta + L_q \cos^2\theta \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + p \begin{bmatrix} 0 & r_m/\omega_r \\ -r_m/\omega_r & 0 \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} r_1 + r_m + pL_d & -\omega_r L_q + pK_{rm} \\ \omega_r L_d - pK_{rm} & r_1 + r_m + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (2)$$

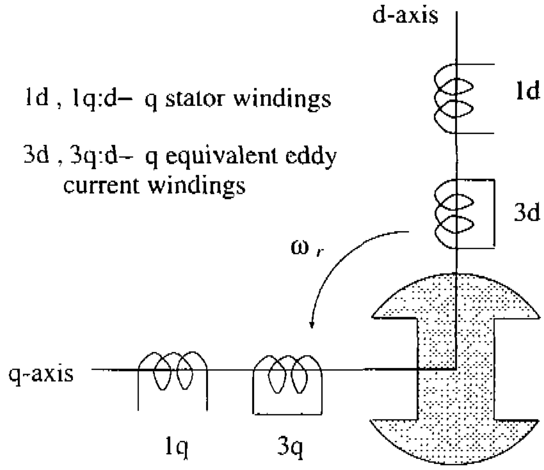

Fig. 1. *d-q* winding model.

where v, i, ω_r and θ are the voltage, current, rotor angular speed and rotor position, respectively. L, r_1 and r_m represent the inductance, armature resistance and equivalent iron loss resistance, respectively. p is the differential operator and subscripts ds and qs express the d and q winding in the stationary reference frame, respectively. Subscripts d and q express the d and q windings in the rotor reference frame, respectively.

In (1) and (2), unknown parameters L_d, L_q and r_m are measured in this paper, since the armature resistance r_1 is easily measured using the direct voltage method.

3. PARAMETER MEASUREMENT METHOD

In this section, a parameter measurement method is presented to measure the unknown parameters in the voltage equation. Equation (2) is used in the parameter measurement because of measurement in the standstill conditions.

Single-phase test

The machine parameters in (1) and (2) must be known because vector control and analysis are based on the voltage equation. Therefore, we execute the measurement of them. The *d-q* axis inductances and the equivalent iron loss resistance in the voltage equation are measured by the single-phase test that is executed in standstill condition. In this method, the Syn. RM is brought into standstill condition with the connection as shown in Fig. 2, and the single-phase sinusoidal voltage is applied to the motor directly when the angular difference between a-phase winding axis and d axis is

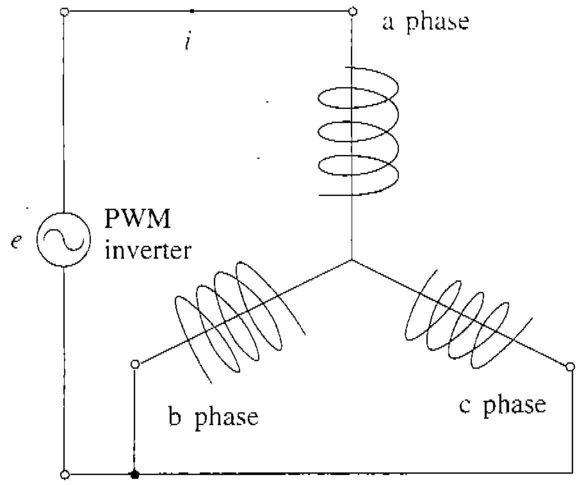

Fig. 2. Connection configuration.

90° and 0° respectively. Then, the phase voltage, phase current, and active power are measured, and the equivalent circuit parameters, L_d, L_q, and r_m are calculated by using the measured values.

Figure 3 shows the relationship between d-q axes and three-phase winding axes. When θ is equal to 0°, a-phase winding axis on the stator is aligned with d axis of the motor. And when θ is equal to 90°, a-phase winding axis on the stator is aligned with q axis of the motor. The rotor position, 0° or 90°, is determined following instructions:

$\theta = 90°$:

The dc voltage source is applied to between the b phase winding and the c phase winding as shown in Fig. 4. Then, the rotor position becomes $\theta = 90°$.

$\theta = 0°$:

The dc voltage source is applied to between the b phase and c phase windings as shown in Fig. 5. Then, the rotor position becomes $\theta = 0°$.

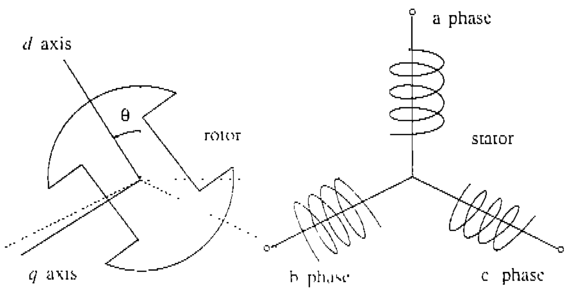

Fig. 3. Relationship between d-q axes and three-phase winding axes

Thus, the rotor position, $\theta = 0°$ or $\theta = 90°$, is determined using the dc voltage source only because the rotor d axis reluctance is smaller than q axis reluctance.

Then, from Fig. 3, three-phase voltages and currents become as

$$v_a = e - v_b = e - v_c, \quad v_b = v_c. \tag{3}$$

$$i_a = i, \quad i_b = i_c = -\frac{i}{2}. \tag{4}$$

From (3), the voltage v_{ds} and v_{qs} in the stationary reference frame is given as

$$\begin{aligned} v_{ds} &= \sqrt{\frac{2}{3}}\left\{v_a - \frac{1}{2}(-v_b) - \frac{1}{2}(-v_c)\right\} \\ &= \sqrt{\frac{2}{3}}e \end{aligned} \tag{5}$$

$$\begin{aligned} v_{qs} &= \sqrt{\frac{2}{3}}\left(\frac{\sqrt{3}}{2}v_b - \frac{\sqrt{3}}{2}v_c\right) \\ &= 0. \end{aligned} \tag{6}$$

And the current i_{ds} and i_{qs} in the stationary reference frame is given as

$$\begin{aligned} i_{ds} &= \sqrt{\frac{2}{3}}\left(i_a - \frac{1}{2}i_b - \frac{1}{2}i_c\right) \\ &= \sqrt{\frac{3}{2}}i \end{aligned} \tag{7}$$

$$\begin{aligned} i_{qs} &= \sqrt{\frac{2}{3}}\left(\frac{\sqrt{3}}{2}i_b - \frac{\sqrt{3}}{2}i_c\right) \\ &= 0. \end{aligned} \tag{8}$$

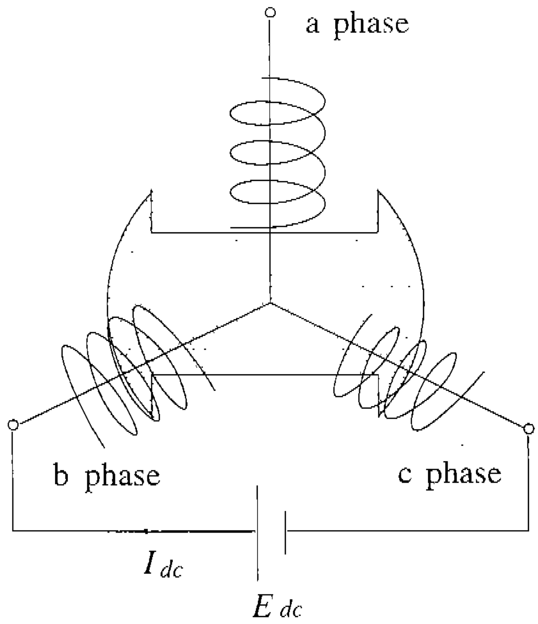

Fig. 4. Stator winding connection configuration.

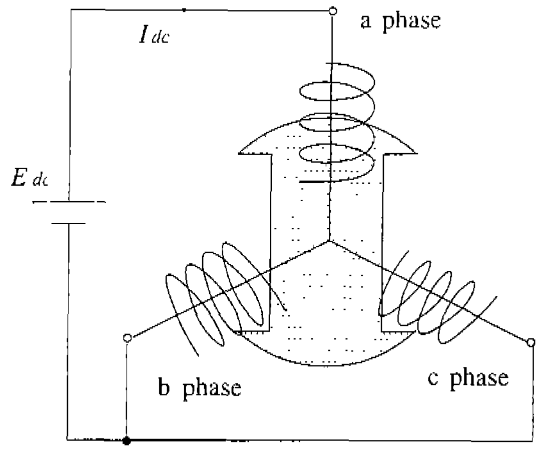

Fig. 5. Stator winding connection configuration.

Equations at $\theta = 90^\circ$

When the single-phase sinusoidal voltage is applied to the a-phase winding on the stator at $\theta = 90^\circ$, the voltage equation becomes as

$$v_{ds} = (r_1 + r_m)i_{ds} + pL_q i_{ds} + p\frac{r_m}{\omega_r}i_{qs}. \tag{9}$$

Substituting (9) into (5) to (8), the voltage equation is obtained as

$$e = \frac{3}{2}(r_1 + r_m)i + p\frac{3}{2}L_q i. \tag{10}$$

In steady state condition, the differential operator p can be replaced by $j\omega_e$ in the voltage equation. Thus, (10) becomes as follows

$$\dot{E} = \frac{3}{2}(r_1 + r_m)\dot{I} + j\frac{3}{2}\omega_e L_q \dot{I}. \tag{11}$$

From (11), the apparent power is yielded as follows

$$\begin{aligned} \dot{E}\bar{\dot{I}} &= P + jQ \\ &= \frac{3}{2}(r_1 + r_m)|\dot{I}|^2 + j\frac{3}{2}\omega_e L_q|\dot{I}|^2. \end{aligned} \tag{12}$$

From (12), the equivalent iron loss resistance r_m and q axis inductance L_q are derived as

$$r_m = \frac{2P}{3I^2} - r_1 \tag{13}$$

$$L_q = \frac{2Q}{3\omega_e I^2}. \tag{14}$$

Equations at $\theta = 0^\circ$

When the single-phase sinusoidal voltage is applied to the a-phase winding at $\theta = 0^\circ$, the voltage equation becomes as

$$v'_{ds} = (r_1 + r_m)i'_{ds} + pL_d i'_{ds} + p\frac{r_m}{\omega_r}i'_{qs} \tag{15}$$

Substituting (15) into (5) to (8), the voltage equation is obtained as

$$e' = \frac{3}{2}(r_1 + r_m)i' + p\frac{3}{2}L_q i'. \tag{16}$$

In steady state condition, the differential operator p can be replaced by $j\omega_e$ in the voltage equation. Thus, (16) becomes as follows

$$\dot{E}' = \frac{3}{2}(r_1 + r_m)\dot{I}' + j\frac{3}{2}\omega_e L_q \dot{I}'. \tag{17}$$

From (17), the apparent power is yielded as follows

$$\begin{aligned} \dot{E}'\bar{\dot{I}}' &= P' + jQ' \\ &= \frac{3}{2}(r_1 + r_m)|\dot{I}'|^2 + j\frac{3}{2}\omega_e L_q|\dot{I}'|^2. \end{aligned} \tag{18}$$

From (18), the equivalent iron loss resistance r_m and q axis inductance L_q are derived as

$$L_d = \frac{2Q'}{3\omega_e I'^2} \tag{19}$$

Accordingly, all the machine parameters in the voltage equation considering stator iron loss can be measured by the single-phase test only.

4. EXPERIMENTAL RESULTS

Experimental results are illustrated to confirm the validity of the proposed measurement method. The three phase voltage source PWM inverter utilizes IGBT modules as power switching devices, and its switching frequency is 16.7 kHz. The tested motor employed in this experiment is the three-phase Syn. RM of which the specifications are given in Table 1. Using the direct voltage method, the armature resistance is 11.575 Ω per phase.

Table 1. Specifications of tested Syn. RM.

rated power	200 W
rated voltage	220 V
rated current	1.2 A
pole number	4

Parameter measurement results

Figures 6 and 7 show the *d*-*q* axis inductances versus armature current characteristics at 40Hz and 60Hz, respectively. In these figures, we can see that *d* axis inductances decrease with the increase of armature current due to the magnetic saturation. And the same characteristics is obtained for the different frequencies.

Figure 8 shows the equivalent iron loss resistance versus frequency characteristics. In this figure, we can see that the equivalent iron loss resistance increases with the increase of frequency. And there is no dependence upon armature current values; we obtained the same characteristics for the different armature current. Thus, we can confirm that the consideration of iron loss is important issue because the increase of driving frequency under high-speed operation leads the iron loss.

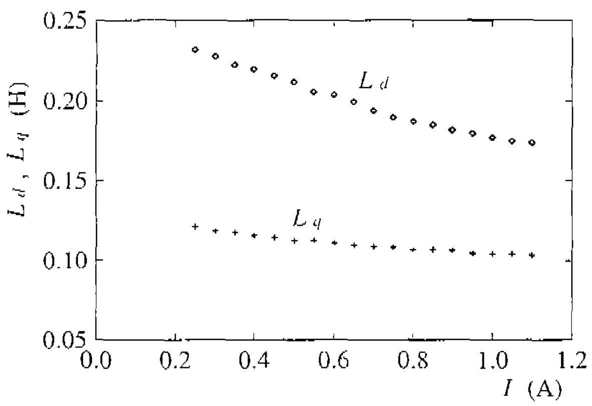

Fig. 6. *d*-*q* axis inductances versus armature current characteristics at 40Hz.

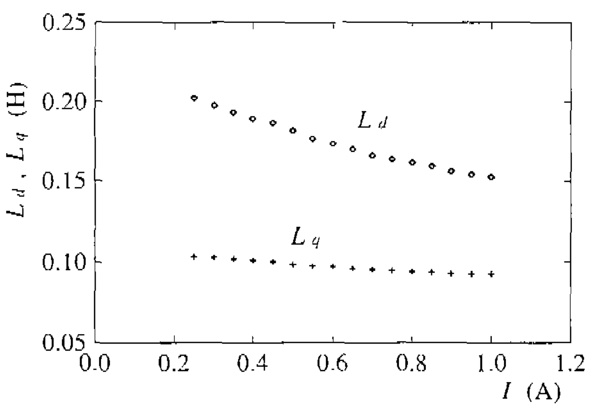

Fig. 7. *d*-*q* axis inductances versus armature current characteristics at 60Hz.

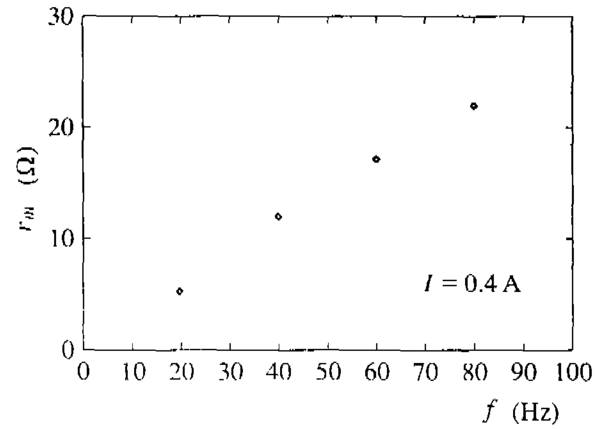

Fig. 8. Equivalent iron loss resistance versus frequency characteristics.

Validity of the measured parameters

To confirm the validity of the measured parameters, relationship between the active power and current is used, which is represented by

$$\begin{aligned} P &= 3(r_1 + r_m)I^2 \\ &+3\frac{(r_1 + r_m)X_q}{(r_1 + r_m)^2 + X_q^2}(X_d - X_q)I^2. \end{aligned} \tag{20}$$

Equation (20) is derived by using (2) and vector diagram[5] for Syn. RM.

Figures 9 and 10 show measured values of active power when Syn. RM is driven in steady state condition and calculated value of active power obtained by substituting the measured parameters into (20). In these figures, there is a slight error in between measured value and calculated value. The reason is that the harmonic components and the rotor iron loss which generate in the standstill condition are neglected. However, the calculated value is approximately in agreement with the measured value.

Therefore, using the proposed measurement method we are confirmed that *d*-*q* axis inductances and equivalent iron loss resistance can easily be measured.

5. CONCLUSIONS

In this paper, to measure the unknown parameters (*d* axis inductance L_d, *q* axis inductance L_q, and equivalent iron loss resistance r_m) for Syn. RM considering stator iron loss, we propose a single-phase test without using neutral point of stator winding. This method is simple and does not need to use complex mathematical theory and equations, because this measurement

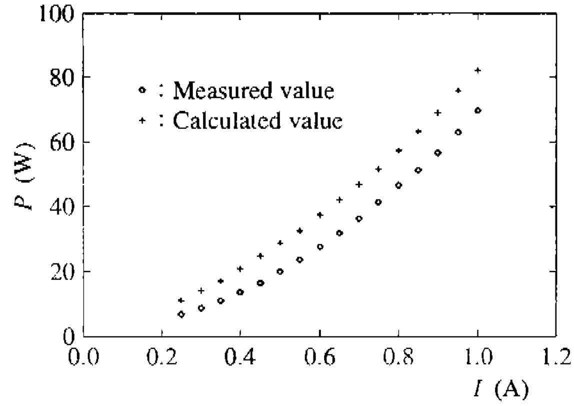

Fig. 9. Active power versus current at 40Hz characteristics.

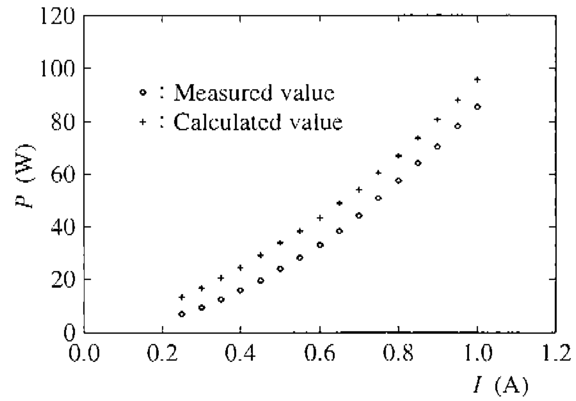

Fig. 10. Active power versus current at 60Hz characteristics.

s achieved at standstill condition without any expen-ive equipment. Experimental results confirm that all nachine parameters in the voltage equation considering he stator iron loss for Syn. RM can easily be measured ısing the single-phase test.

6. REFERENCES

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