Parameter Measurement of Induction Motors

Kyung-Seo Kim, Sung-Hoon Byun, Seung-Ho Na, Byung-Guk Cho and Bong-Hyun Kwon
LG Industrial Systems, Co.
533 Hogae-Dong, Dongan-Gu, Anyang, Korea

Abstract - This paper presents the parameter measurement methods for high performance drive of induction motors. The proposed methods are selected by considering the factors that affect accuracy of measurement. Each method are refined to be adequate for measurement of each motor parameters. Proposed methods are easy to implement and only require inverter-motor system, which are important for practical application.

1. Introduction

Most of vector control or sensorless vector control methods make use of equivalent motor model, so that the performance of these kind of drives highly depend on the accuracy of parameter values of induction motors. Lots of commercial drive systems with vector control has auto-measuring function which is inevitable for high performance drives.

Traditional method for measuring motor parameters is locked rotor test and no-load test. But this method requires extra methods that can lock the rotor or rotate the rotor in synchronous speed. These kinds of methods are not practical for commercial purpose. The other methods to measure motor parameter by inverter alone are test signal injection, MRAS, single phase excitation, etc. But these methods assume motors to be ideal machine and measurement conditions to be ideal also. But there are many factors that affect the variation of machine parameters and accuracy of measurement results. Some characteristics of machine which are not expressed in equivalent circuit of motors largely affect measurement results, depending on which measurement method or measuring conditions are used. Also inverter has many nonlinear factors such as characteristics of switching devices, dead time effect, accuracy of sensors, etc.

In this study, the factors which affects the accuracy of parameter measurement are examined, then, measuring methods which fit to each parameters of motors are proposed.

2 . Measurement of motor parameters

2.1 Equivalent circuit of induction motors

Fig.1 shows equivalent circuit used for parameter measurement. Inverse-gamma type circuit is convenient to calculate variables because there remains only active component R_r' in rotor circuit.

Magnetizing inductance, rotor resistance and rotor time constant are newly defined as follows.

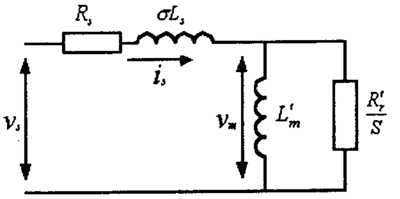

Fig. 1 Equivalent circuit of induction motors

$$L_m' = L_m^2 / L_r = L_s(1-\sigma) \tag{1}$$

$$R_r' = R_r \frac{L_m^2}{L_r^2} \tag{2}$$

$$T_r = L_r / R_r = L_m' / R_r' \tag{3}$$

2.2 System setup

All measurement functions are implemented in LGIS general purpose inverter, iS5-series. Main control function of these inverters is V/f control, and indirect vector control and sensorless vector control are optional. Main processor of these inverters are TMS320F240, 16bit fixed point DSP. Power switching devices are IGBT, and switching frequency is 10kHz nominal.

Test motor is 7.5kW induction motor, and it's rating is as table1.

Table 1. Rating of test motor

Type	GoldStar KMI10HK1
Capacity	7.5 [kW]
Rated Voltage	380 [V]
Rated Current	15.2 [A]
Rated Speed	1730 [rpm]

2.3. Measurement of stator resistance

Most convenient method to measure stator resistance using inverter is to apply DC voltage to motor terminals, then measure the motor current. Measured value through this method is sum of stator resistance and equivalent inverter resistance. Because total sum of stator resistance and inverter equivalent value is required for motor control, this method is more adequate to inverter-motor system. In real system there are dead time effect and voltage drop of switching devices which causes DC offset in measured value. DC offset can be removed by measuring the voltage and the current in two point, then, calculating resistance by eq.(4).

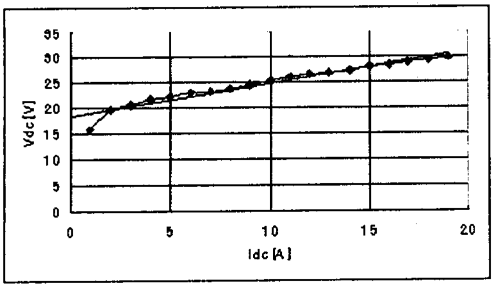

Fig. 2 Measurement of stator resistance

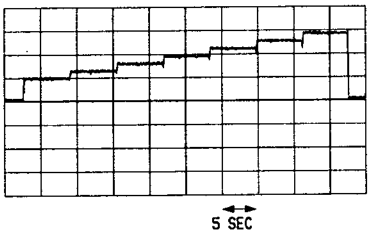

Fig. 3 Excitation current for measuring stator resistance

$$R_s = \frac{(V_{s2} - V_{offset}) - (V_{s1} - V_{offset})}{I_{s2} - I_{s1}} = \frac{V_{s2} - V_{s1}}{I_{s2} - I_{s1}} \qquad (4)$$

In eq(4), DC offset is canceled and does not affects the calculation of stator resistance. But this is true only if DC offset is constant through whole operating range. DC offset is not constant and equivalent resistance including inverter equivalent resistance varied according to the variation of DC current level.

Fig.2 shows variation of equivalent resistance according to current level. If two points are selected in vicinity of 50% of rated current, equivalent resistance value is calculated as 0.6[ohm]. But if measuring point moves to vicinity of rated current, equivalent resistance value decrease to 0.5[ohm]. In this case how to select the measuring points causes more than 20% difference of measuring results.

To overcome this problem, several point are selected as measuring points, then find straight line which approximate measured points. Bold line in fig.2 is approximated line. The slope of this line is taken to be equivalent stator resistance. Least square approximation method is adopted to acquire straight line which is close to measuring points. Least square approximation method used in this study is from reference[6]. The equation to calculate equivalent resistance using least square approximation is as follows.

$$R_s = l_0 V_s[0] + l_1 V_s[1] + \cdots + l_7 V_s[7] \qquad (5)$$

where $l_0 \ldots l_7$ is pre-calculated constants using reference[6], and $V_s[0] \ldots V_s[7]$ is measured voltage for each current level.

Fig.3 shows the measurement process of resistance. Current level begins with 30% of rated current and increase 10% for each step. In each step, voltage is measured 40,000 times, then average voltage is calculated from this data.

2.4. Measurement of leakage inductance

Single phase voltage is applied to motor terminals, motor is in stand-still, so that slip frequency is same as frequency of applied voltage. If the frequency is enough high, impedance of magnetizing inductance is much higher than rotor resistance value, which means that the magnetizing circuit can be omitted in equivalent circuit. Then, equivalent circuit of fig.1 can be simplified to fig.4. Difference of calculation results between fig.4 and fig. 1 is under 0.5% which is negligible in practical use.

If single phase sinusoidal voltage of eq. (6) is applied to motors, there flows lagging current in motor phase. This phase current can be divided into active current component and reactive current component. Active component has same phase with applied voltage and reactive component lag 90 degree. Active current component $I_{P(rms)}$ and reactive current component $I_{Q(rms)}$ can be calculated using eq.(7) and eq.(8).

$$v_s = V_s \sin(\omega_e t) \qquad (6)$$

$$I_{P(rms)} = \frac{1}{\sqrt{2}\pi} \int_0^{2\pi} i_s \sin(\omega_e t) d\theta \qquad (7)$$

$$I_{Q(rms)} = \frac{-1}{\sqrt{2}\pi} \int_0^{2\pi} i_s \cos(\omega_e t) d\theta \qquad (8)$$

$$V_{s(rms)} = V_s / \sqrt{2} \qquad (9)$$

$V_{s(rms)}$ is rms value of applied voltage.

Leakage inductance σL_s and total resistance R_r' can be calculated from eq.(10) and eq.(11) , where P is active power and Q is reactive power.

$$\sigma L_s = \frac{Q}{\omega_e {I_{s(rms)}}^2} = \frac{I_{Q(rms)} V_{s(rms)}}{\omega_e (I_{P(rms)}^2 + I_{Q(rms)}^2)} \qquad (10)$$

$$R_r' + R_s = \frac{P}{I_{s(rms)}^2} = \frac{I_{P(rms)} V_{s(rms)}}{(I_{P(rms)}^2 + I_{Q(rms)}^2)} \qquad (11)$$

If high frequency signal is injected, slip frequency also has high frequency value, which is much higher value than rated slip. This affects the variation of rotor resistance if rotor has deep bar or double cage structure. Fig.5 shows this effect. Leakage inductance has no concern with frequency change. On the other hand, rotor resistance value changes according to variation of frequency of applied voltage.

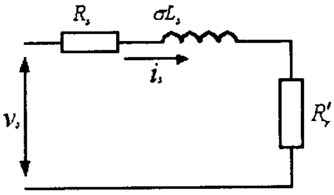

Fig. 4 Modified equivalent circuit with high frequency excitation

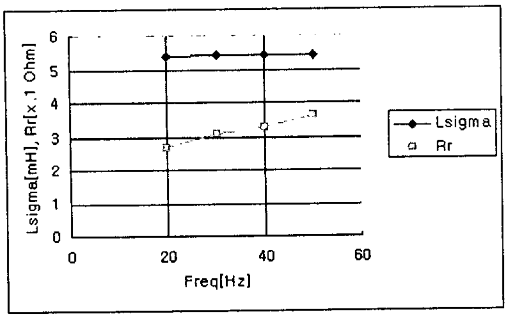

Fig. 5 Leakage inductance and rotor resistance with frequency change

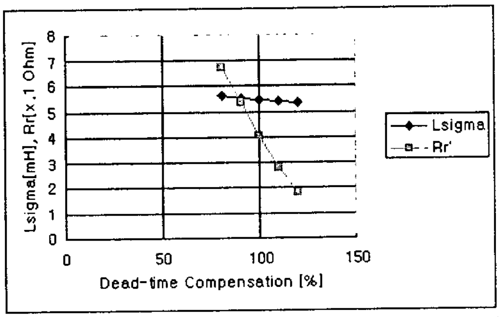

Fig. 6 Leakage inductance and rotor resistance with dead-time compensation voltage

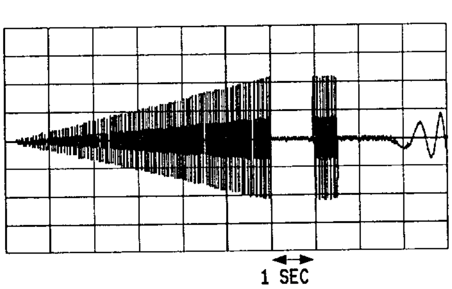

Fig. 7 Single phase voltage for leakage inductance measurement

Dead-time effect also affects the measurement of rotor resistance. Fig.6 is variation of leakage inductance and rotor resistance when dead-time compensation voltage is varied from 80% to 120%. In fig.6, variation of leakage inductance is not much compared with variation of rotor resistance. The reason why the variation of rotor resistance is high according to the variation of dead-time compensation voltage is that compensation voltage is same as current phase, so that the dead time voltage only affect the variation of active power if only fundamental component is considered.

From above results it can be concluded that only leakage induction can be measured correctly by single phase excitation method.

Fig.7 shows single phase voltage and current waveforms. Voltage is gradually increased until current reach the desired value. After then reactive power is measured from current and voltage.

2.5 Measurement of magnetizing inductance and magnetizing current

Most of high performance drive has current control loop. Therefore it should be guaranteed that supply voltage must be lower than rated voltage even though motor run in rated speed and rated load condition.

If magnetizing current is measured by no-load test with applying rated frequency and rated voltage and this current value is used as reference value of magnetizing current, current may be uncontrollable under rated load. Because there is not enough voltage margin required for current control. Another problem of no-load test is that no-load test requires a equipment which enable test motor to run in synchronous speed. This is not practical method for auto-measurement function of inverter.

For practical usage, more convenient method which can be done by inverter alone. It may be possible to calculate air-gap voltage in rated load condition by using name plate values of test. Assuming that the stator resistance and leakage inductance are already known, air-gap voltage $v_{m(rated)}$ of fig.1 under rated load can be calculated like below.

$$\bar{v}_{m(rated)} = v_{s(rated)} - (i_{s(rated)}\cos\varphi + j i_{s(rated)}\sin\varphi)(R_s + j\omega_{e(rated)}\sigma L_s) \quad (12)$$

where $v_{m(rated)}$ is the voltage of magnetizing circuit under rated speed $\omega_{e(rated)}$, rated voltage $v_{s(rated)}$ and rated current $i_{s(rated)}$. If $v_m = v_{m(rated)}$, magnetizing current I_m and rotor flux is always constant regardless of load variation and v_s is always lower than $v_{s(rated)}$ even in full load condition.

Measurement begins with acceleration of motor until motor speed reach to rated speed. Once motor speed reach to rated speed and supply voltage become rated value, supply voltage v_s decrease until v_m equal to $v_{m(rated)}$.

v_m is calculated by eq.(13).

$$\begin{aligned}\vec{v}_m &= v_{m(real)} + j v_{m(imag)} \\ &= v_s - (i_{s(real)} + j i_{s(imag)})(R_s + j\omega_{e(rated)}\sigma L_s)\end{aligned} \quad (13)$$

When $v_m = v_{m(rated)}$, magneting current can be calculated as follow equation.

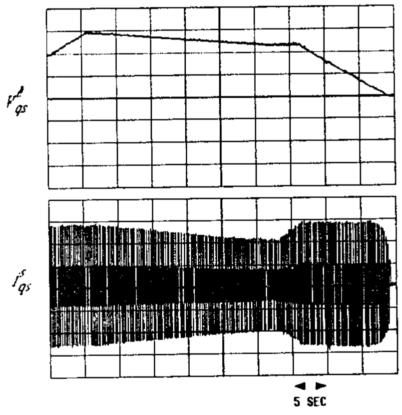

Fig. 8 Voltage magnitude(upper) and phase current(lower) during measurement of magnetizing current and inductance current

$$i_{m(rated)} = i_m = \frac{v_{m(real)} i_{s(imag)} - v_{m(imag)} i_{s(real)}}{v_m} \qquad (14)$$

Magnetizing inductance is calculated at the same time as follows.

$$L'_m = \frac{v_{m(rated)}}{i_{m(rated)} \omega_{e(rated)}} \qquad (15)$$

Fig.8 is voltage magnitude and phase current during measurement of magnetizing inductance.

2.6. Measurement of rotor time constant

For measuring rotor time constant, a method which compare real variables and reference variables from reference model is used. Among various reference models, d-axis voltage reference model is most sensitive to the variation of rotor time constant [2]. Eq.(16) is d-axis reference voltage under field oriented condition.

$$v_{ds}^{e*} = R_s i_{ds}^e - \omega_e L_\sigma i_{qs}^e \qquad (16)$$

To measure rotor time constant, indirect vector control is used as control method. If rotor time constant is exactly known so that slip gain has correct value, measured d-axis voltage coincide with d-axis reference voltage of eq.(16).

There need small amount of load for measuring rotor time constant. Because, if slip is too small, there is no difference between d-axis voltage with correct slip gain and d-axis voltage with incorrect slip gain. To apply load to test motor is not so easy in practical application. To make loaded condition, rotor inertia is used as load by accelerating test motor for short interval.

Measuring sequence is as follows. Before starting, rated magnetizing current applied, then torque reference is applied as reference value. During acceleration error voltage is measured from measured d-axis voltage and reference voltage. If motor speed reach to maximum speed, motor decelerates to stop. This sequence repeats for number of times.

MRAC can be used for adaptation of rotor time constant[2]. But, in order to guarantee the convergence, it is necessary to tune the parameters of MRAC block. Another difficulty of adaptive method is that convergent time is not predictable.

In this study, direct measurement method is used. After applying torque reference, error voltage is measured during acceleration, then motor decelerates to stop. This acceleration/deceleration cycle repeat number of times. Slip gain increase in each cycle. Fig.9 shows measuring sequence mentioned above. And fig.10 shows the variation of d-axis voltage with increase of slip constant. Slip constant begins with 70% of initial value and increase to 130% with 5% step. In each step, error voltage is measured every 10 mSEC then average value is calculated from these data. At the beginning cycle, real d-axis voltage is lower than reference d-axis voltage. Real d-axis voltage increases with advance of cycle. Real d-axis voltage is close to reference d-axis voltage in point 'A' of fig.10, where slip constant is close to exact value. Exact slip constant lies in the point where error become zero.

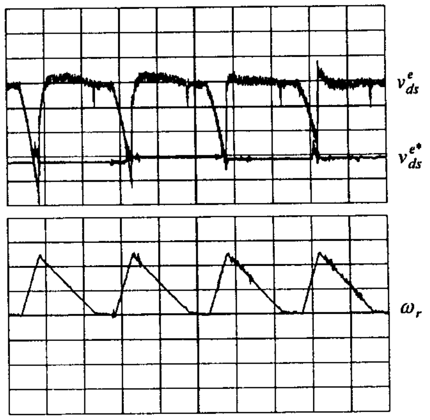

Fig. 9 D-axis voltade and rotor speed during slip constant measerement

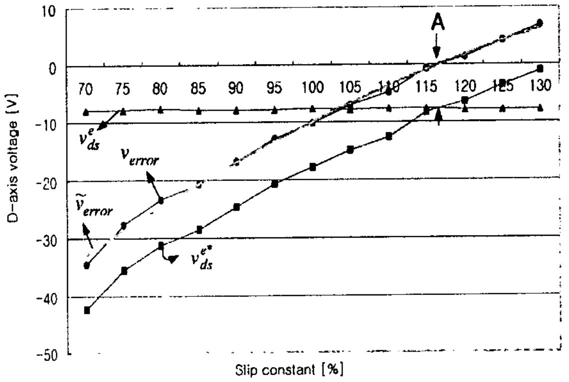

Fig. 10 Approximation of d-axis error voltage

To find out exact value of slip constant, measured points are approximated to 2-nd order curve. For this, least square approximation of reference[6] is used. The equation to calculate slip constant using least square approximation is as follows.

$$V_{err} = a_0 + a_1 K_{s(n)} + a_2 K_{s(n)}^2 \quad , n = 70, 75 \ldots 130 \qquad (5)$$

$$a_0 = [l_0, l_1, \ldots, l_{13}][V_{err}(0), V_{err}(1), \ldots, V_{err}(13)]^T$$

$$a_1 = [m_0, m_1, \ldots, m_{13}][V_{err}(0), V_{err}(1), \ldots, V_{err}(13)]^T$$

$$a_2 = [n_0, n_1, \ldots, n_{13}][V_{err}(0), V_{err}(1), \ldots, V_{err}(13)]^T$$

where $[l_0, l_1, \ldots, l_{13}]$, $[m_0, m_1, \ldots, m_{13}]$, $[n_0, n_1, \ldots, n_{13}]$ is pre-calculated constants using the method in reference[6], and $[V_{err}(0), V_{err}(1), \ldots, V_{err}(13)]$ is measured voltage for each cycle.

Thick gray line of fig.10 is approximation curve, and the exact value is on cross point of $\tilde{v}_{error}$ and x-axis. If slip constant K_s is measured, rotor time constant T_r can be calculated as follows.

$$T_r = 1 / K_s \qquad (17)$$

In proposed method, time for measurement is always 13 cycles and exact value can be always found if it lies within ±25% of initial value.

2.7. Experimental result

Table 2. is measurement result for the motor of table 1. Measured value is compared with reference value. Reference values are from no-load test, torque linearlity test and response comparison. Reference values are obtained by indirect method, so that it is questionable that reference values can be considered as real values.

To verify the measured value, these parameters were applied to real system which has sensorless vector control and indirect vector control function block. Performance of this system showed that the proposed method can measure motor parameters that are very close to real values.

Table 2. Experimental result

Motor Parameters	Measured value	Reference Value
R_s	0.522 [ohm]	0.518 [ohm]
σL_s	10.1 [mH]	11.5 [mH]
$I_{m(rms)}$	5.4 [A]	6.34 [A]
L_s	92.3 [mH]	91.2 [mH]
T_r	0.288 [sec]	0.264 [sec]

3. Conclusion

This paper presents the parameter measurement methods for high performance drive of induction motors. The aim of this study is to develop a parameter measurement method for commercial inverter, which need to be reliable and could be done by inverter alone. For this, adequate method for each parameters is developed which consider the factors causing measurement error. Experimental result of proposed method shows similar results during several repetition, and values of measured parameters are close to real parameter values.

References

[1] K. Yanagawa, K. Sakai, S. Ishida, T. Endou and H. Fujii, "Auto Tuning for General Purpose Inverter with Sensorless Vector Control", IPEC-Yokohama, pp.1005-1009, 1995

[2] T.M.Rowan, R.J.Kirman and D.Leggare "A Simple On-Line Adaptation for Indirect Field Orientation of an Induction Machine", IEEE Trans. On Industral Appl.., Vol.27, No.4, 1991

[3] M. Ruff and H. Grotstollen, "Off-line Identification of the Electrical Parameters of an Industrial Servo Drive System", IEEE IAS'96, pp.213-220, 1996

[4] C. Millet, J. Pierguin and C. Bergmann, "Identification of a Small Power Induction Machine", EPE'99 Records, pp. p.1-p.7, 1999

[5] Peter Vas, *Parameter Estimation, Condition Monitoring and Diagnosis of Electrical Machines*, Clarendon Press, pp.180-306 1993

[6] C. Gerald and P. Wheatley, *Applied Numerical Analysis*, Addison Wesley, pp.534-540, 1984