Induction Machine Parameter Identification using PWM Inverter at Standstill

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Abstract -- **This paper presents a new approach to identify the induction machine parameters using the PWM inverter. For the field oriented control of induction machine, accurate induction machine parameters are necessary. Usually, the inverter utilizes the machine parameters supplied from the manufacturer or estimated by extraneous tests. To overcome this problem, the proposed method utilizes the PWM inverter itself for machine parameter identification at standstill. All the test procedures are performed and the parameters are identified by the PWM inverter and its own controlling computer. The proposed method has been implemented on actual inverter systems and thoroughly tested on two different induction machines to confirm its feasibility.**

I. Introduction

Recently, many research efforts have been spent in developing high performance AC drives for the induction machine in accordance with critical industrial demands. As a result of these efforts, a fast dynamic response of induction machine can be achieved by the field oriented control. Several different configurations are suggested for the field oriented control according to the flux positioning method. Among them, the indirect rotor flux oriented control is known as an attractive candidate due to its simple structure and effective decoupling characteristics [1].

In the indirect rotor flux oriented control, the rotor flux position is obtained by adding the measured rotor angle to the computed slip angle, where the latter quantity gives the position of the rotor flux relative to the direct axis of the rotor. The performance of the indirect rotor flux oriented control is strongly depends on the accuracy of the slip angle which can be calculated from the reference values of the torque, the flux producing the stator currents, and the rotor parameters. For this computation, the rotor parameter values of the machine under consideration should be used. Therefore, in order to get the rotor flux position correctly, the accurate rotor circuit parameters are necessary. When incorrect parameter values are used in the controller, it may cause instantaneous errors in both torque and flux resulting in sluggish dynamics. Thus, it is essential to have accurate parameters of the induction machine in order to achieve the ideal instantaneous torque control [1-2].

Traditionally, the induction machine parameters were obtained by performing locked rotor and no load tests. However, in many industrial fields, it is very difficult to perform these tests because the machine is usually coupled to the mechanical load [3]. Moreover, under the locked rotor test at rated frequency, the skin effect can heavily influence the accuracy of the rotor resistance [4]. More recently, the time domain and the frequency domain standstill tests are proposed [5-6]. But these methods also require special test equipments and extensive test procedures.

In this paper, a novel standstill parameter identification method for induction machine driven by voltage source PWM inverter is presented. In this method, all tests and parameter estimation procedures are performed by the PWM inverter and its own controlling computer without aids of any extra equipments. The proposed scheme can be implemented on an existing controller by just adding software program only. Also, the parameters can be effectively estimated under any mechanical loading condition. With this parameter identification scheme on the controller, an inverter can be utilized for any induction machine although whose parameters are unknown.

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II. Induction Machine Model

Induction machine dynamics are usually modeled by equivalent circuits in the synchronous rotating reference frame as shown in Fig. 1. The voltage equations of the induction machine are as follows:

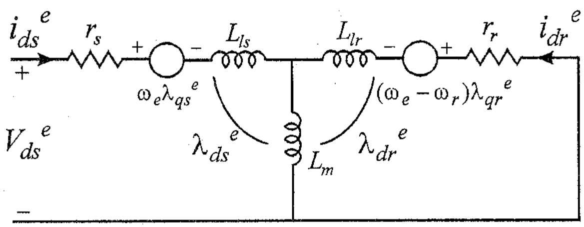
$$V_{ds}^{e} = r_s i_{ds}^{e} + p\lambda_{ds}^{e} - \omega_e \lambda_{qs}^{e} \tag{1}$$

$$V_{qs}{}^{e} = r_s i_{qs}{}^{e} + p\lambda_{qs}{}^{e} + \omega_e \lambda_{ds}{}^{e} \quad (2)$$

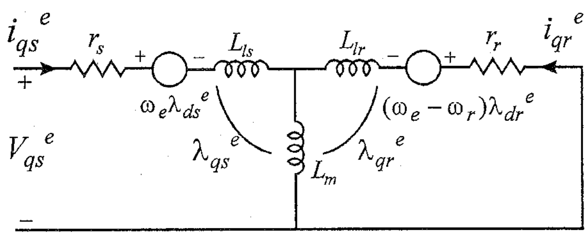
$$0 = r_r i_{dr}{}^{e} + p\lambda_{dr}{}^{e} - (\omega_e - \omega_r)\lambda_{qr}{}^{e} \quad (3)$$

$$0 = r_r i_{qr}{}^{e} + p\lambda_{qr}{}^{e} + (\omega_e - \omega_r)\lambda_{dr}{}^{e} \quad (4)$$

In the above equations, V_{ds}^{e}, V_{qs}^{e}, i_{ds}^{e} and i_{qs}^{e} indicate the d and q axis terminal voltages and the stator currents, respectively. λ_{ds}^{e}, λ_{qs}^{e}, λ_{dr}^{e} and λ_{qr}^{e} represent the d and q axis stator and rotor flux. ω_e is the synchronous angular velocity and ω_r is the rotor electrical angular velocity. And, r_s is the stator resistance, r_r is the rotor resistance and p represents the differential operator.



(a) d-axis circuit



(b) q-axis circuit

Fig. 1. Equivalent circuit of induction machine in synchronously rotating reference frame

III. Identification Method

The proposed parameter estimation technique is to be implemented on a practical inverter system which is controlled by the indirect rotor flux oriented control method. All the tests and the parameter estimation procedure will be performed by the inverter and its own controller only. Thus, in practical parameter estimation aspect, the following restrictions should be considered: 1) the inverter has only current sensors, 2) the rotor of the machine may be mechanically coupled to the load, 3) the test should be simple enough to be reliably repeated on different machines and 4) the parameter estimation algorithm should be robust enough to estimate the parameters in the presence of heavy inverter switching noises. Considering this, the following standstill test procedure is developed.

A. Rotor Resistance Identification

The d-axis equivalent circuit of the induction machine at standstill can be drawn as Fig. 2. In order to identify the rotor resistance, the d and q axis currents are controlled in the stationary reference frame according to the following relationships:

$$i_{ds}{}^{s} = I_{ds} + I_h \sin\omega_h t \quad (5)$$

$$i_{qs}^{s} = 0 \quad (6)$$

On the d-axis, a sinusoidal current with DC bias is applied while the q-axis current is controlled to be zero. The DC bias current I_{ds} is determined as the nominal current value given on name plate. The sinusoidal current term has a constant frequency ω_h and amplitude I_h. When the frequency ω_h is high enough, most of the DC current I_{ds} flows through the L_m branch while the sinusoidal current $I_h \sin\omega_h t$ flows through the rotor branch.

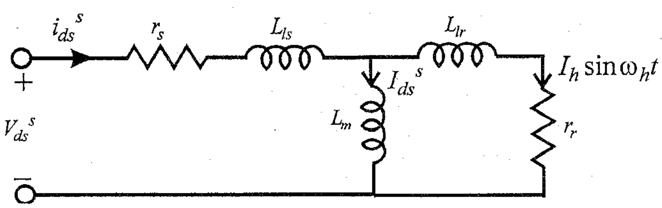


Fig. 2. d-axis equivalent circuit for rotor resistance identification

The mutual inductance L_m, rotor leakage-inductance L_{lr}, and rotor resistance r_r can be approximately obtained from name plate data [7]. With these values, the frequency ω_h is determined using the following condition:

$$\frac{|r_r + j\omega_h L_{lr}|}{|j\omega_h L_m|} \le 0.05 \quad (7)$$

From Fig. 1, the following voltage equations are derived.

$$V_{ds}{}^{s} = r_s i_{ds}{}^{s} + L_{ls}\frac{d}{dt} i_{ds}{}^{s} + L_{lr}\frac{d}{dt}(I_h \sin\omega_h t) + r_r (I_h \sin\omega_h t) \quad (8)$$

$$\begin{aligned} V_{ds}{}^{s} - r_s I_{ds} &\cong (r_s + r_r) I_h \sin\omega_h t + L_\sigma I_h \omega_h \cos\omega_h t \\ &= C I_h \sin(\omega_h t + \alpha_h) \end{aligned} \quad (9)$$

$$C = \sqrt{(r_s + r_r)^2 + (\omega_h L_\sigma)^2}, \alpha_h = \tan^{-1} \frac{\omega_h L_\sigma}{r_s + r_r} \quad (10)$$

where L_σ is the stator transient inductance.

From the above relationship, the phase difference α_h between $I_h \sin\omega_h t$ and $V_{ds}{}^s - r_s I_{ds}$ includes the information of the rotor resistance. In other words, from the equation (10), r_r is obtained as

$$r_r = \frac{\omega_h L_\sigma}{\tan\alpha_h} - r_s \quad (11)$$

Therefore, the rotor resistance can be uniquely determined by detecting the corresponding phase difference α_h. For identifying r_r, the stator resistance r_s and the stator transient inductance L_σ need to be known. The equivalent stator resistance r_s including ohmic drop of power devices is obtained by the following DC tests [8]. DC current is forced into the machine and the ratio of voltage to current is computed to get the stator resistance r_s. The same test with a different level of DC current is performed again to eliminate the nonlinear effects of the inverter such as dead time and current sensor scaling. The average value of these is used as the stator resistance r_s in the equation (11). The stator transient inductance L_σ is identifiable by determining the current slope when a step voltage is applied across the machine terminals [9]. A voltage pulse is applied to the machine by selecting an arbitrary switching state of the inverter for few micro second. Under this condition the rate of flux change for this small time interval is almost zero and the following relationships will hold:

$$V_{qs}{}^s = r_s i_{qs}{}^s + L_\sigma \frac{di_{qs}{}^s}{dt} \cong L_\sigma \frac{di_{qs}{}^s}{dt} \quad (12)$$

$$L_\sigma = V_{qs}{}^s \frac{\Delta t}{\Delta i_{qs}{}^s} \quad (13)$$

Therefore, L_σ is obtained by using the peak-to-peak current $\Delta i_{qs}{}^s$, the time Δt for the current change and the applied voltage.

B. Rotor Time Constant Identification

For the rotor time constant identification, the inverter supplies a constant DC current on the *d*-axis of the stator winding while keeping the *q*-axis current zero. And then, the stator terminals are shorted by turning-on all three upper switches or all three lower switches of the inverter. The decaying stator current trajectory is measured through the current sensors. Considering the equivalent circuit shown in Fig. 1, the dynamic equations of the d-axis current can be expressed as

$$Vds = rs \cdot Ids + Lls \frac{dIds}{dt} + Lm \frac{dIds}{dt} + Lm \frac{dIdr}{dt} \quad (14)$$

$$0 = rr \cdot Idr + Llr \frac{dIdr}{dt} + Lm \frac{dIdr}{dt} + Lm \frac{dIds}{dt} \quad (15)$$

Then, the stator and the rotor winding current will be represented as the following exponential functions:

$$Ids = A \cdot e^{-t/T1} + B \cdot e^{-t/T2} \quad (16)$$

$$Idr = -C \cdot e^{-t/T1} + C \cdot e^{-t/T2} \quad (17)$$

Here, the first term in the equation (16) represents the fast changing portion of the response and the second term corresponds to the slowly changing portion. By applying the equations (16) and (17) into the equations (14) and (15), and comparing the coefficients of each exponential function, the rotor and the stator time constants can be obtained as

$$Tr = \frac{L_{lr} + Lm}{rr} = \frac{A \cdot T2 + B \cdot T1}{A + B} \quad (18)$$

$$Ts = \frac{Lls + Lm}{rs} = \frac{A \cdot T1 + B \cdot T2}{A + B} \quad (19)$$

The equations (18) and (19) indicate that the required rotor time constant can be estimated if the measured stator current is fitted to the exponential function given in equation (16).

However, from the actual tests on various machines, some problems are observed. First, due to the conducting voltage drop of the IGBT's and the free wheeling diodes in the inverter, when shorting the stator terminals by turning-on all three upper switches or all three lower switches of the inverter, the stator current is negatively biased. This brings down the overall stator current trajectory, and makes the slowly changing portion of the decaying current unobservable. In most cases, it is found that the stator current reaches to zero in about 0.2 second, and it makes the estimation of B and T2 parameters in the equation (16) difficult. Second, due to the skin effects, the rotor resistance becomes larger during the fast changing response at the beginning of the test. This affects the estimation of A and T1 parameters in the equation (16).

To overcome the above problems, the test procedure is modified as follows: 1) instead of shorting the stator terminals, a sinusoidal voltage with small magnitude is applied and 2) only the slowly changing portion of the current response is utilized for the estimation by discarding the fast changing portion to prevent the skin effects. In this case, the parameters A and T1 are not estimated. Thus, the rotor time constant needs to be obtained by the parameters B and T2 only.

For the slowly changing portion of the response, the stator and the rotor current can be expressed as

$$Ids \approx B \cdot e^{-t/T2} \tag{20}$$

$$Idr \approx \frac{rs}{rr} \cdot Ids = k \cdot Ids = k \cdot B \cdot e^{-t/T2} \tag{21}$$

Here k indicates the ratio of the stator and the rotor resistance, and it can be obtained as discussed in the previous section. By applying the equations (20) and (21) into the equation (15), and comparing the coefficient of the exponential function, the following relation for the rotor time constant is obtained

$$Tr \approx \frac{Lm}{rr} = \frac{k \cdot T2}{(k+1)} \tag{22}$$

For the curve fitting of the slowly changing portion of the response, the d-axis stator current is expressed as

$$\hat{Ids} = B \cdot e^{-t/T2} + C \tag{23}$$

Here, C indicates the DC current bias term due to the unsymmetry of the inverter. The parameters to be estimated are

$$\theta = [B \quad C \quad T2] \tag{24}$$

As a estimation algorithm, the simplex method suggested by Nelder and Meade is utilized [10]. This method does not utilize the derivatives, thus the convergence rate is relatively slow. But it is very robust and reliably converges to the parameter values even in the presence of heavy measurement noises.

IV. Experimental Results

Extensive tests are performed to evaluate the feasibility of the proposed identification method. The algorithm is programmed and installed on two different inverters; one drives 22 kW induction machine and the other drives 5 HP machine. The parameter values of these machines were already known. Also, these parameters had been utilized for the indirect rotor flux oriented control and their accuracy was verified. Table 1 shows these known parameter values. The estimated parameter values will be compared to these values to verify the feasibility of the proposed method. The overall experimental set-up is shown in Fig. 3. The switching devices in the inverter are IGBT's with 5 kHz switching frequency. The DC link voltage is 300 V and the sampling period of current control is 100 μsec. Using the space vector PWM scheme with dead time compensator, the terminal voltage measurement is not required, thus the voltage sensors are not equipped. TMS320C31 DSP is used as main control processor, which operates with 33.33MHz clock and is capable of 33.33 mega floating point operations in each second. All the internal data of DSP can be displayed on the oscilloscope through a multi-channel 12 bit D/A converter.

Table 1. Ratings and known parameters of test induction machines

Rated power output	5 HP	22 kW
Rated line voltage	220V	220V
Number of pole	4	4
Supply frequency	60 Hz	60 Hz
r_s	0.55 Ω	0.04 Ω
r_{rV}	0.356 Ω	0.024 Ω
L_m	59 mH	13.24 mH
L_σ	4.2 mH	1.1 mH

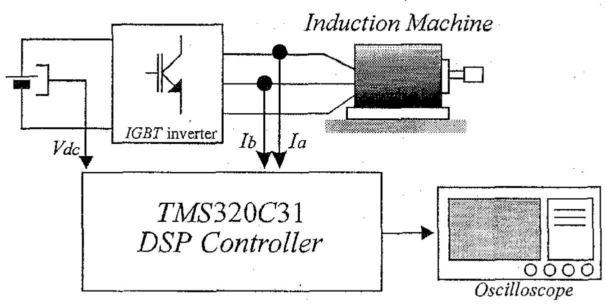


Fig. 3. Experimental system configuration

A. Rotor Resistance Identification

Fig.4 shows the actual waveforms of $V_{ds}{}^{s} - r_s I_{ds}$ and $I_h \sin \omega_h t$ which are measured from 5 HP machine test. The phase difference of these two waveform is α_h as described in equation (9). In order to eliminate the ripples from the output voltage and the DC offset from the current measurements, a lowpass filter with 100 Hz cutoff frequency and a highpass filter with 5 kHz cutoff frequency are utilized for $I_h \sin \omega_h t$ and $V_{ds}{}^{s} - r_s I_{ds}$ waveforms, respectively. The injected test signal frequency is selected as 20 Hz for 5 HP machine and 10 Hz for 22 kW machine. With these signals, the inequality condition (7) is satisfied for both machines. The amplitude of sinusoidal current I_h is selected as half of the DC bias current I_{ds}. In Fig.5, the trajectory of estimated rotor resistance of 5 HP induction machine is depicted. This clearly shows that the estimated value converges in about 5 seconds.

To examine the rotor bar skin effect according to the injected signal frequency variation, several tests are performed on 22 kW machine with test signal frequencies between 9 and 20 Hz. The result is illustrated in Fig. 6. This figure clearly shows that the rotor resistance increases as the signal frequency increases. Also, it is found that the estimated resistance value is acceptable compared to known value at the selected test frequency.

Table 2 presents the estimated values for the rotor resistance, stator resistance r_s and stator transient inductance L_σ of two different machines obtained from three different tests. In the table, r_{rT} is the value obtained from the locked rotor test and r_{rV} is obtained from the laboratory tuning considering the field oriented control performance. The estimated values from this proposed test are represented as r_{rst}. In each test, the percentage difference between r_{rst} and r_{rV} is within 20%. The identified value is reasonably accurate for performing the proper field oriented control.

b. Rotor Time Constant Identification

Once the rotor and the stator resistance values are estimated, the stator and rotor resistance ratio k is determined. The inverter supplies a constant DC current I_b at the beginning of the test, and then applies sinusoidal test signal expressed as

$$v(t) = V_m \sin(2\pi f t + \pi) \quad (25)$$

instead of shorting the stator terminals. Fig.7 shows the measured stator current of 5 HP machine. The initial DC current I_b is chosen by considering the stator rated current and current sensor maximum scale. The voltage signal magnitude V_m is selected as the resulting stator current is limited to few percents of the rated value. Extensive tests were performed to select optimal values of the test signal frequency f, and it is found that frequencies between 200 Hz and 400 Hz are proper.

Table 3 presents the estimated rotor time constants of 5 HP and 22 kW machines. Each machine is tested three times and the results are compared to the known rotor time constant values. The results show that the differences between the known values and the estimated values are within 20%, and consistent estimated values are obtained.

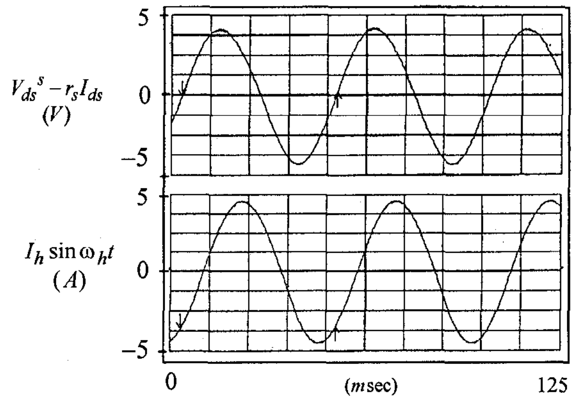


Fig. 4. Phase difference between $I_h \sin\omega_h t$ and $V_{ds}^s - r_s I_{ds}$

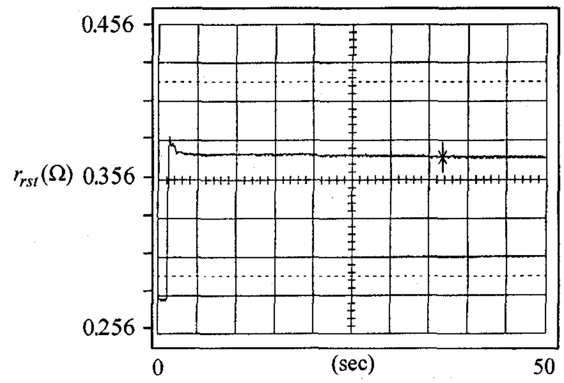


Fig. 5. Trajectory of estimated rotor resistance

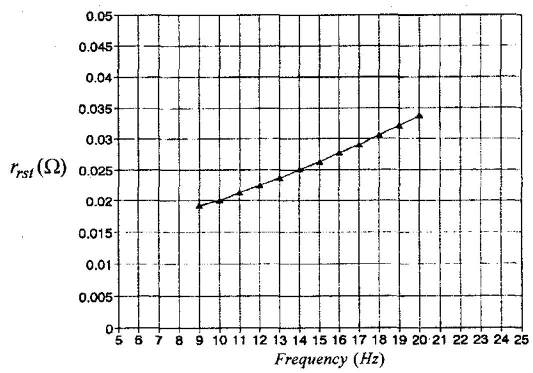


Fig. 6. Rotor resistance variation according to the test signal frequency change.

V. Conclusion

This paper presents a new approach to identify the induction machine parameters using PWM inverter. The proposed method estimates the stator, rotor resistance and rotor time constant of the machine, which are necessary for

Table 2. Test Results of Rotor Resistance Identification

Machine	r_{rT} (Ω)	r_{rV} (Ω)	r_{rst} (Ω)	r_s (Ω)	L_σ (mH)
5Hp	0.52	0.356	0.369	0.548	4.22
			0.366	0.552	4.21
			0.375	0.559	4.17
22kW	0.0623	0.024	0.0209	0.0401	1.09
			0.0192	0.0402	1.11
			0.0213	0.0399	1.10

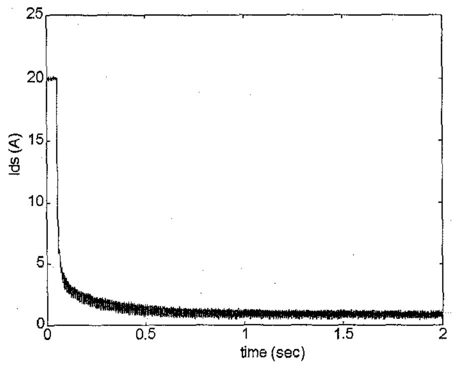


Fig. 7 Measured stator current response of 5 HP machine

Table 3. Estimated rotor time constant

		5HP	22kW
$V_m(V)$		2	5
f (Hz)		240	240
$Ib(A)$		20	150
Known	T_r(sec)	0.165	0.552
Estimated T_r(sec)	test 1	0.139	0.586
	test 2	0.144	0.557
	test 3	0.138	0.609

the field oriented control. It utilizes only the inverter and its own controlling computer, and the test can be performed regardless the mechanical loading of the machine. Thus, this method makes it possible to apply an inverter to any induction machine for rotor flux oriented control even though machine parameters are unknown. For verification, the algorithm is implemented on two different inverter systems and its feasibility is confirmed by the tests. The test results show that the proposed method can estimate parameter values consistently, and the differences between the known parameter values and the estimated values are within 20 %.

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