Off-line Parameter Estimation of Induction Motor for Vector Control In Continuos Process Line

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Abstract - **Parameter estimation method of induction motor for vector control is presented in this paper. It can be easily implemented and applied to inverters in the industrial field, because it needs no additional hardware such as voltage sensors and measuring equipment. The proposed algorithm in this paper is so straightforward and practical that it can be easily implemented on the built-in controllers with little overhead. The proposed estimation algorithm has good accuracy and repeatability for parameters due to the sensitivity of estimation errors. This enables its total consuming time to be made shorter. Experimental results and applications in the industrial fields verify the validity and usefulness of the proposed method.**

I. Introduction

In recent years, the vector-controlled inverter of induction motor has been increasingly applied to the drive system that requires high performance torque control capability. It is important to know accurate electrical parameters of induction motor for high performance drive system

The parameters of induction motor can be approximately obtained through the nameplate data and classical methods such as no load test and locked rotor test. However, the obtained parameters in this way can not be used for high performance drive system due to its deviation from real parameters. They also have a problem that tuning process is time-consuming to adjust parameters. A number of schemes for parameter indentification have been made to overcome the above problems[1] [2].

The presented method of parameter estimation can be easily implemented and applied to inverters in industrial field, because it needs no additional hardware such as voltage sensors and measuring equipments. It requires only a little software modification.

The stator resistance can be determined by a test at constant dc voltage output, where the applied voltage-to-current ratio is measured. However, the actual voltage is less than its calculated value due to nonlinear term such as dead time of inverter, loss of switching device and freewheeling diode. Making several measurements at different dc levels can separate out the error due to the nonlinear influence. We can get the linear approximation from voltage-current measurement data by using least square method. The slope is the stator resistance while intercept includes the nonlinear effect.

The accuracy and repeatability of parameter estimation in this paper highly depend on the synthesis of an output voltage. Due to the nonlinear behavior of PWM-VSI such as dead-time, the offset of current sensor, and voltage drop across switching device, it is necessary to provide some compensation methods[3] [4]. By implementing online dead time compensation the difference between a calculated output voltage and an actual output voltage can be minimized.

The rotor time constant can be estimated by observing the transient response of motor terminal voltage. The rated torque current is forced to the machine for some interval until the machine reaches to a preset rotating speed. In all time the d-axis constant field current is imposed for pre-magnetizing the machine. The estimation algorithm of rotor time constant begins after turning off torque command. From the stator voltage equation, we know that its transient response caused by the undesirable variation of rotor flux is a time varient (exponentially decreasing) term. This time-variant term is closely related with the inverse of rotor time constant. We introduce the update rule for the inverse of rotor time constant so that the rotor time constant can be guickly converged to its real value if possible.

The transient (leakage) inductance, stator inductance, and moment of inertia can be measured at the other interval of the same operation as the rotor time constant estimation. It is possible to measure inductance and inertia simultaneously from the relations between voltages and speed feedback, and between output torque and speed feedback, respectively.

II. STATOR RESISTANCE MEASUREMENT AND DEAD-TIME COMPENSATION

A. Stator Resistance Measurement

The stator resistance is measured by applying dc voltage to stator. The commanded voltage output of current controller includes not only a voltage drop across the stator resistance but also voltage drop across switching device, nonlinear behavior of dead-time, and the offset of A/D converters and CT(current transducer)s[4] .

The commanded voltage output can be written as follows.

$$\begin{aligned} v_{out} &= (r_{stator} + r_{switch}) \cdot i_{out} + (v_{dead} + v_{offset}) \\ &= \alpha \cdot i_{out} + \beta \end{aligned} \quad (1)$$

where

v_{out} : a commanded voltage output of current controller

i_{out} : an actual current feedback

v_{dead} : a nonlinear voltage term due to dead-time

v_{offset} a nonlinear voltage term due to the sensor offset

From equation (1) the slope is the stator resistance of an induction motors including switching loss, and the intercept of y-axis indicates the voltage drop caused by nonlinear terms.

The measurement procedure is as follows. After applying a constant voltage corresponding to 5% level of rated current, measuring data are acquired. At this time some waiting period is necessary to avoid the influence of transients during measurement. Next, applying constant voltage increments by 5% until stator current reaches to the rated value. The stator resistance can be calculated from measuring data set using least mean square method.

B. Dead-time Compensation

Earlier mentioned, the accuracy of the current sensor and the quality of synthesized output voltage are very important to make good performance of the proposed algorithm in this paper. The offset caused by the nonlinearity of current sensor can be measured during initial system startup. It is easy to eliminate offset.effect by subtracting the measured offset value from the sensing value. Then the nonlinear term in the output voltage can be minimized by on-line dead-time compensation as the following.

$$T_{DT\_COMP}(k) = T_{DT\_COMP}(k-1) + \frac{\beta(v_{out}, i_{out})}{V_{dc}} \cdot T_s$$

where

$T_{DT\_COMP}(k)$: Dead-time compensation at k[th] sample time

V_{dc} : DC link voltage

T_s : Sampling period

III. ROTOR TIME CONSTANT ESTIMATION

The rotor time constant considerably affects the performance of vector control system. It is estimated in the following way. The rated torque current is forced to the machine for some interval until the machine reaches to preset rotating speed. In all time the d-axis constant field current is imposed for magnetizing the machine. The operation for estimation of rotor time constant is shown in Fig. 1. In this figure, the time-variant term of d-axis stator voltage is calculated for interval A after torque command is turned off.

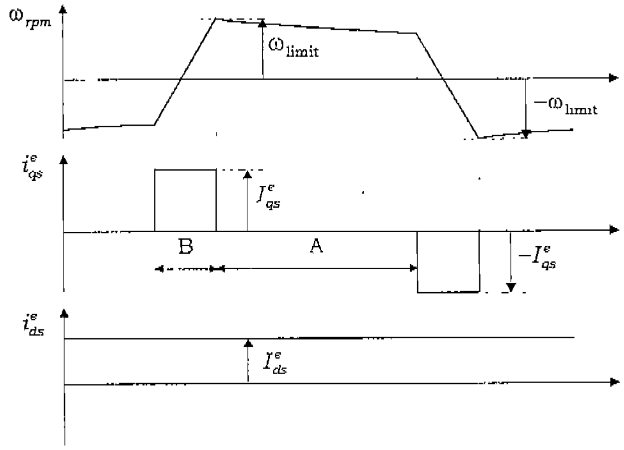

Fig. 1 Operation for estimation of rotor time constant.

From voltage equations of equivalent circuit for induction motor, the stator d-axis voltage equation can be derived as follows:

$$v_{ds}^e(t) = r_s I_{ds}^e + \Delta v_{ds}^e(t)$$

$$\Delta v_{ds}^e(t) = -\left(\frac{L_m}{L_r}\right) e^{-\left(\frac{r_r}{L_r}\right)t} \left\{ \frac{r_r}{L_r}\left(\lambda_{dr}^e(t_0) - L_m I_{ds}^e\right) + \omega_r \lambda_{qr}^e(t_0) \right\} \quad (2)$$

Assuming all conditions for the vector control are satisfied, that is,

$$\lambda_{dr}^e(t_0) = L_m I_{ds}^e \quad (3)$$

$$\lambda_{qr}^e(t_0) = 0 \quad (4)$$

From the equation (2) the d-axis stator voltage becomes the product of the stator resistance and the d-axis stator current at any instant time. If the estimated rotor time constant is mismatched, the time-decreasing term $\Delta v_{ds}^e(t)$, which is due to the undesirable variation of rotor flux, does not zero any more. That is

$$\lambda^e_{qr}(t_0) \neq 0 \tag{5}$$

It is possible to know whether the estimated rotor time constant is matched to its real value by observing the transient response of the d-axis stator voltage. It is also possible to get the physical insight of the rotor time constant from speed response[5] .

To make the estimation procedure of rotor time constant automatic, the following update rule is introduced.

$$\frac{1}{\tau_r(n)} = \left[1 - K_1\, atan\left(\sum \Delta v^e_{ds}\right)\right]\frac{1}{\tau_r(n-1)} \tag{6}$$

where

K_1 : Gain constant for change rate of ($1/\tau_r$)

$\sum \Delta v^e_{ds}$: Sum of the time decreasing term Δv^e_{ds} during pre-defined interval.(about 3~5 times of rotor time constant)

The final step is to determine the necessary boundary for finishing the tuning of rotor time constant. The indirect flux oriented scheme based on calculation of slip speed is used in the proposed estimation algorithm. The calculation of flux angle is as the following equation.

$$\hat{\theta}_e = \int \omega_r dt + \int \left(\frac{1}{\hat{\tau}_r}\frac{I^e_{qs}}{I^e_{ds}}\right) dt \tag{7}$$

The relations of the estimated rotor time constant, q-axis rotor flux, and time-variant term of d-axis stator voltage Δv^e_{ds} is shown Table I. The vector diagrams of rotor flux and the responses of d-axis stator voltage during tuning are shown in Fig. 2. It is seen from this figure that in correct case of the estimated rotor time constant Δv^e_{ds} is almost 0, in excessive case Δv^e_{ds} is negative, and in insufficient case Δv^e_{ds} is positive.

Table I The relationship of estimated rotor time constant, q-axis rotor flux, and time-variant term of d-axis stator voltage

Estimated rotor time constant	q-axis rotor flux	Time variant term of d-axis stator voltage
$1/\hat{\tau}_r < 1/\tau_r$	$\lambda^e_{qr}(t_0) > 0$	$\Delta v^e_{ds} < 0$
$1/\hat{\tau}_r = 1/\tau_r$	$\lambda^e_{qr}(t_0) \approx 0$	$\Delta v^e_{ds} \approx 0$
$1/\hat{\tau}_r > 1/\tau_r$	$\lambda^e_{qr}(t_0) < 0$	$\Delta v^e_{ds} > 0$

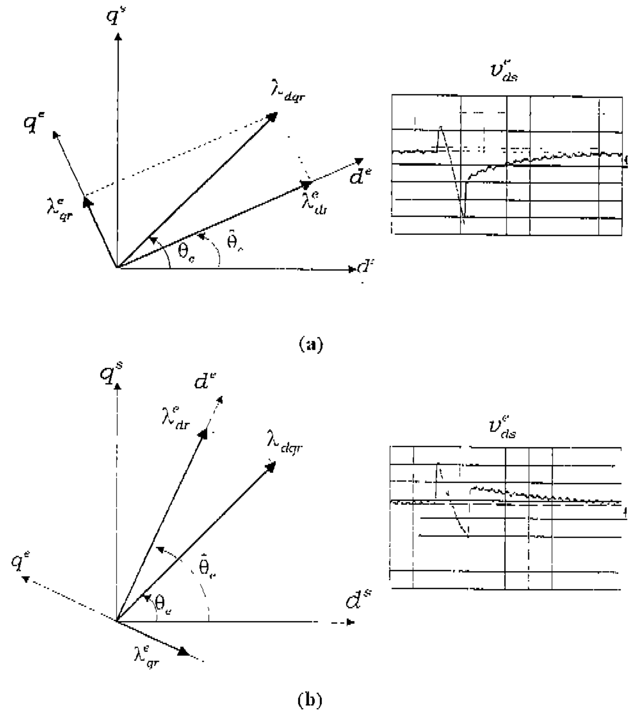

Fig. 2 The vector diagrams of rotor flux and the responses of v^e_{ds}. From top: (a) in case of excessive rotor time constant, (b) in case of insufficient rotor time constant

III. INDUCTANCES AND INERTIA MEASUREMENTS

A. Transient(Leakage) Inductance & Stator Inductance

The measurement of inductance and inertia is carried out for interval B in Fig. 1. If the rotor time constant is estimated accurately and field orientation conditions are satisfied. The stator voltage equations can be written as follows:

$$v^e_{ds} = \left(r_s i^e_{ds} - \omega_{sl} L_\sigma i^e_{qs}\right) - \omega_r L_\sigma i^e_{qs} \tag{8}$$

$$v^e_{qs} = \left(r_s i^e_{qs} + \omega_{sl} L_s i^e_{ds}\right) + \omega_r L_s i^e_{ds} \tag{9}$$

From the above equations, if the slopes of voltages and angular velocity of rotor are found, it is possible to measure the inductance using the following equations. The slopes are calculated by least mean square method.

$$L_\sigma = \frac{\text{slope}(v^e_{ds}, \omega_r)}{i^e_{qs}} \tag{10}$$

$$L_s = \frac{\text{slope}(v^e_{qs}, \omega_r)}{i^e_{ds}} \tag{11}$$

B. Momentum of Inertia

The last parameter of motor to be measured is not electrical but mechanical. Usually it can be read from nameplate data, but if manufacturer does not provide it and mechanical loads such as roll and reduction gear are added, the following classical scheme is very useful. The inertia is important parameter that is included in gains of

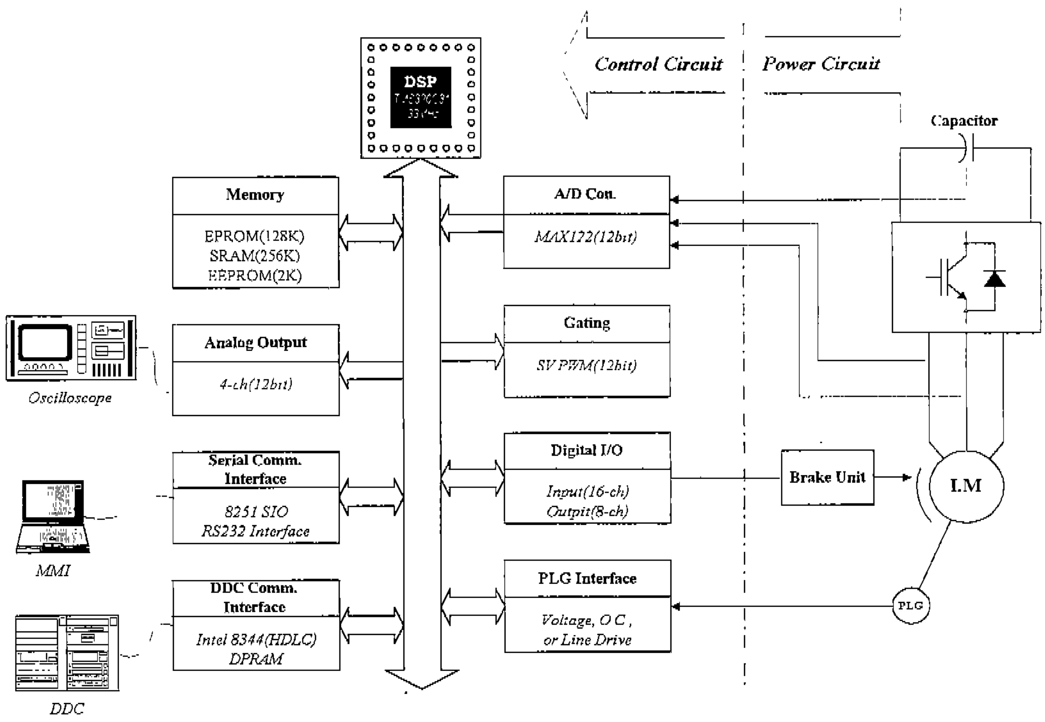

Fig. 3 System configuration of experiment setup

speed controller to get desired speed response. From a simple mechanical model, the following equation can be derived.

$$T_e = J_m \frac{d\omega_r}{dt} \tag{12}$$

$$J_m = T_e \frac{\Delta t}{\Delta\omega_r} \tag{13}$$

The measurement of inductance and inertia can be done simultaneously for B interval in Fig. 1 when torque is applied to the machine It is noted that the measurements are done for the interval except from turn-on and turn-off instance of torque command to avoid the influence of transients.

IV. EXPERIMENT RESULTS

To verify the proposed off-line parameter estimation scheme in this paper, the algorithm was implemented on a built-in system by only a little modification of software. We use a commercial inverter and standard NEMA-B machine, the ratings of which are listed in Table II. The nameplate data of the machine is read into the initialization module while the system is booting. Also a user through MMI (man-machine interface) can feed these data before the program begins.

Table II Ratings of the induction machine used in experiment

Rated power output[kW]	22
Rated voltage[V]	440
Rated current[Arms]	39.7
Number of poles	4
Base speed[r/min]	1770
Rated magnetizing current[A]	17

The parameter estimation and control algorithm were developed on a TI digital signal processor (TMS320C31-33MHz) system. The PWM strategy based on space vector PWM[7] is used and its switching frequency is 2.5 kHz. The incremental encoder (4096 pulses/rev) is used for measuring the angular speed of rotor. The system configuration of experiment setup is shown in Fig. 3.

Table III shows the performance of proposed algorithm. The parameters of induction motors were the average values of 10 measurement data and the maximum errors were calculated based on these average values. From this table, it is verified that our algorithms have a good accuracy and repeatability.

Table III The average values of estimated parameters and maximum error

Parameter	Average value	Maximum error[%]
r_s [Ohm]	0.1458	2.34
$1/\tau_r$ [1/sec]	4.45	1.28
L_r [mH]	3.48	2.87
L_s [mH]	40.06	0.4
J_m [kg m^2]	0.165	1.12
T_{DT_COMP} [usec]	2.66	4.25

To examine the control characteristics using these estimated parameters; we had several tests that include step response, operation in the range of constant torque, and the operation in field weakening region.

Fig 4 shows step response without ramp of speed command. The former command of rotating speed command is +400[rpm], the latter is –400[rpm]. The operation in the constant torque region (to base speed 1800rpm) is shown in Fig. 5 In this operation, speed ramp function is used. At last, The operation in the field-weakening region(to 2500rpm) is shown in Fig. 6. It is pointed out that the flux controller and the flux estimator are adapted. The indirect flux oriented scheme based on calculation of slip speed was used in the proposed estimation algorithms.

To produce maximum torque per ampere over the entire field weakening region, the field weakening operation is based on the literature[6] .

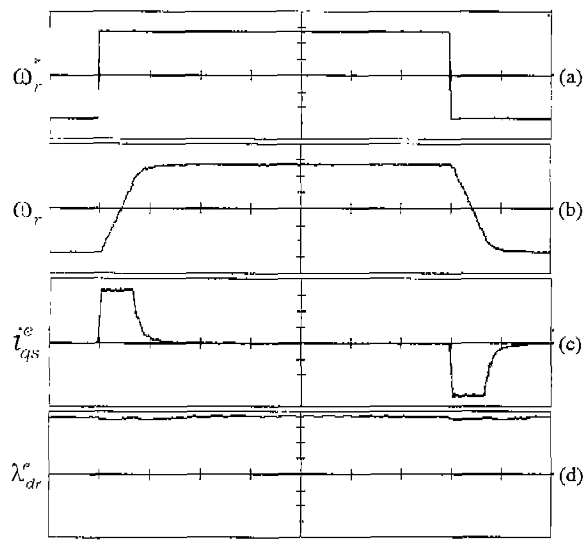

Fig. 4 Step response without speed ramp. From top: (a) speed reference (ω_r^* [rpm]), (b) speed feedback (ω_r [rpm]), (c) q-axis stator current (i_{qs}^e), (d) d-axis rotor flux (λ_{dr}^e)

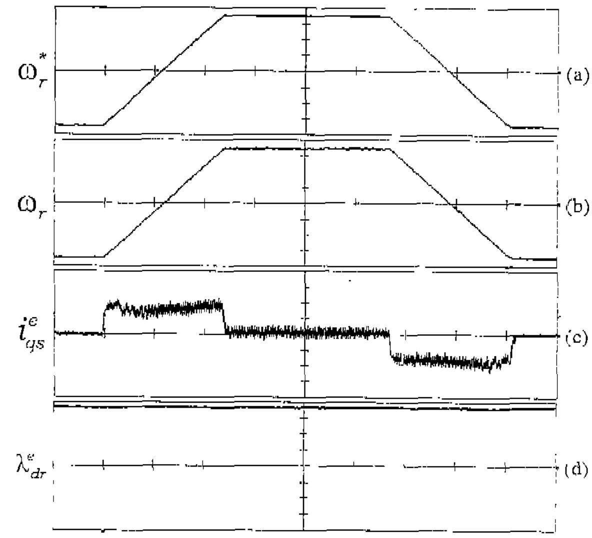

Fig. 5 Operation in constant torque region with ramp speed command. (a) speed reference (ω_r^*), (b) speed feedback (ω_r), (c) q-axis stator current (i_{qs}^e), (d) d-axis rotor flux (λ_{dr}^e)

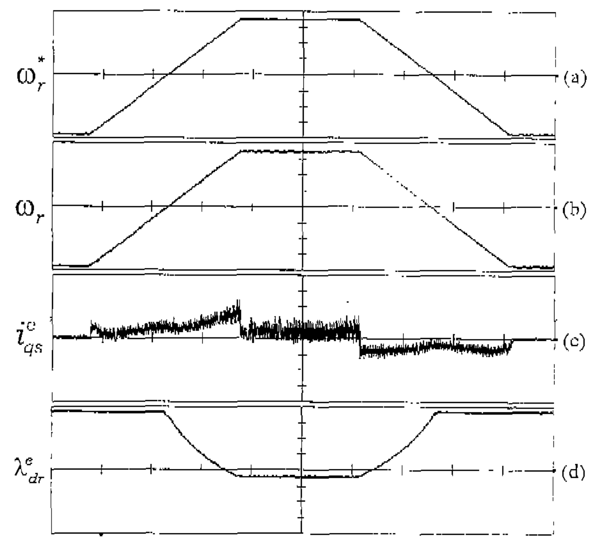

Fig. 6 Operation in constant torque region with ramp speed command. (a) speed reference (ω_r^*), (b) speed feedback (ω_r), (c) q-axis stator current (i_{qs}^e), (d) d-axis rotor flux (λ_{dr}^e)

V. Conclusions

In this paper, we presented the off-line parameter estimation of indution motors. It has been proven that the proposed estimation algorithm has good accuracy and repeatability by experiment. It is also seen that the vector inverter system has high performance when it is operated with the parameter obtained from proposed algorithm. The proposed estimation method is so simple and practical that it has been applied to the commercial vector inverter system in the various fields such as No.2 RCL in the 4th cold mill at Kwangyang Steelworks and the 3rd plate line at Pohang Steelworks of POSCO, Korea.

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