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◉ 論　文

# An Identification Method of Secondary Resistance for Quick Torque Control in Induction Motors

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# 유도전동기의 토크 고속 응답제어를 위한 2차저항 동정법

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**Key Words** : Induction Motor(유도전동기), Secondary Resistance(2차저항), Identification(동정), Quick Torque Control(토크고속제어)

## 요 약 문

최근 유도전동기를 이용한 가변속 구동시스템의 수요가 자동화 및 에너지의 효율적 이용 측면에서 육상 산업체는 문론, 선박 및 해양플랜트에도 확산되고 있다. 유도전동기의 토크 고속제어법은 가변속 구동시스템의 고성능화를 위한 필수과제로서, 제어법 적용시 2차저항의 동정문제가 대단히 중요하다.

본 논문에서는 유도전동기의 토크 고속 응답제어계에 있어서 고정도의 토크응답을 실현하기 위한 2차저항 동정법을 제안한다. 제안된 방법은 모터의 회로방정식으로부터 유도되며, 모터의 인가전압과 1차전류 정보로부터 간단히 구현된다. 제안된 방안의 타당성을 검증하기 위하여 펄스폭변조방식의 전압형 인버터를 상정한 수치 시뮬레이션을 수행하며 그 결과를 통하여 제안방식의 유용성을 입증한다.

## 1. Introduction

In view point of automatization and energy saving, servo systems became indispensable to applications such as industrial robots, numerically controlled machinery and variable speed driving system. Even the field of ship and several marine plant, the needs of this servo system are increased fastly[1]. Especially, induction motors(I.M), particulary the cage type, are widly used as AC servo system because of its ruggedness, low maintenance requirements, reliability, efficiency and low cost.

At the present time, quick torque control methods such as slip frequency type vector control and field oriented vector control enable an induction motor to attain as quick torque response as a DC motor. However, these

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methods require the information of secondary resistance to calculate slip frequency reference or rotor flux. The slip frequency type has higher sensitivity to the secondary resistance than field oriented type[2]. Several methods have been proposed to minimize the effects of parameters variation[3)~5)]. Another approach to overcome this problem, a method based on predictive full-order observer, with variable poles placement, to estimate rotor flux and stator current is investigated. As results, the rotor flux is estimated with very low sensitivity to parameters variation[6].

On the other hand, in view point of transientless torque responses, quick torque control method[7] which is quite different from above mentioned vector controls has been proposed. The method can realize stepwise torque responses with very small and finite settling time. It has two interesting features. One is that the method can determine voltage commands feedforwardly without any current feedback loops. Therefore, it is expected to be applicable very fast torque control system which can not be ignored even current feedback time delay. The other is that the method can be conducted very easily because of its simple arithmetic. However, the control method also requires the real value of rotor resistance to guarantee precise torque responses.

The purpose of this study is to investigate a novel identification method of secondary resistance for the quick torque control of I.M[7]. The proposed method is derived theoretically from motor circuit equation and can be realized very simply by detecting primary currents and by using voltage commands of an I.M. Some numerical simulation results considering pulse width modulation(PWM) inverter will be introduced to prove the validity of the suggested method.

## 2. Quick torque control by voltage controlled inverter

The quick torque control method[7] can realize stepwise torque response with very small and finite settling time $\Delta$ such as shown in Fig. 1 by controlling input voltage pattern in equation (1).

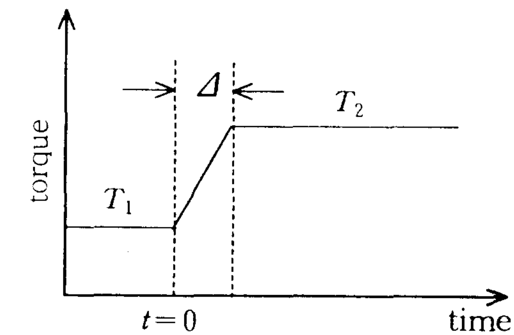



Fig. 1 Desired very quick torque control pattern

$$\boldsymbol{u}(t)=\begin{cases}\boldsymbol{u}_1\exp(j\omega_1 t) & t<0\\ \boldsymbol{u}_2\exp(j\omega_2 t)+\boldsymbol{u}_c & 0\le t<\Delta\\ \boldsymbol{u}_2\exp(j\omega_2 t) & \Delta\le t\end{cases} \qquad (1)$$

where $\boldsymbol{u}_i$ and $\omega_i (i=1,2)$ are the voltage vector and angular frequency before($i$=1) and after($i$=2) torque change, respectively. The pulse vector $\boldsymbol{u}_c$ is added on the sinusoidal voltage $\boldsymbol{u}_2$ during $\Delta$ in order to eliminate transient currents occurred after torque changes. The variables $\boldsymbol{u}_i$ and $\boldsymbol{u}_c$ are complex values, and their real and imaginary part correspond to the $d$ and $q$ axis compenents of two phases expression. The settling time $\Delta$ can be taken less than a couple of milli-seconds if a high speed microprocessor is used for an arithmetic of control algorithm and an assumption that an inverter has enough voltage to output.

Fig. 2 illustrates a phase voltage variation before and after torque change according to (1).

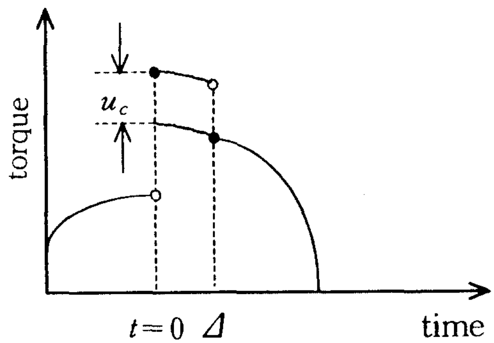



Fig. 2 Voltage variation before and after torque change

In the quick torque control method[7], angular frequency at the time of $n$ is given as

$$\omega_n^* = \frac{\sigma^4 T_n^*}{NR_2 m^2 C^2} + \dot{\theta}_{en} \tag{2}$$

where $N$ is a number of pole pair, $R_2$ secondary resistance, $m$ mutual inductance, $T_n^*$ torque command, and $\dot{\theta}_{en}(=\frac{d\theta_{en}}{dt})$, $\sigma^2(L_1L_2-m^2)$ represent electrical angular velocity and leakage inductance. Notation "*" means reference value. Theoretically the parameter $C$ can have any positive values and it represents the operating point of an I.M. One of the practical ways to determine the value of the parameter $C$ is by idnentifying it from rated operating conditions. Equation (2) is rewritten as (3):

$$T_n^* = \frac{NR_2 m^2 C^2}{\sigma^4}(\omega_n^* - \dot{\theta}_{en}) = K\omega_s \tag{3}$$

where

$$K = \frac{NR_2 m^2 C^2}{\sigma^4}, \quad \omega_s = \omega_n^* - \dot{\theta}_{en}$$

From (3), it is shown that the torque is controlled proportionally to the slip frequency $\omega_s$ by the quick torque control method.

The voltage command at the time of $n$ in the quick torque control[7] is as follows:

$$\boldsymbol{u}_n^* = (\dot{\boldsymbol{u}}_n + \boldsymbol{u}_{cn})\boldsymbol{C}_n \tag{4}$$

$$\dot{\boldsymbol{u}}_n = (\boldsymbol{\tau}_1 + j\omega_n)(\boldsymbol{\tau}_2 + j\omega_n) \tag{5}$$

$$\boldsymbol{u}_{cn} = j(\omega_n - \omega_{n-1})\{1/\Delta - (j\omega_n + \boldsymbol{\tau}_1 + \boldsymbol{\tau}_2)/2\}$$
$$(1 - j\Delta\omega_{n-1}/2)\boldsymbol{C}_n \tag{6}$$

where

$$\boldsymbol{C}_n = \boldsymbol{C}_i \exp(j\Delta\sum_{k=i}^{n-1}\omega_k),$$

$$\boldsymbol{C}_i = C\exp\left\{j(\varphi + \Delta\sum_{k=0}^{i-1}\omega_k)\right\}, \ i < n$$

$$C = \sqrt{\frac{\sigma^4 T_{rat}}{NR_2 m^2(\omega_{rat} - \dot{\theta}_{erat})}}\ )$$

In the above equations, $\boldsymbol{\tau}_i\,(i=1,\ 2)$ means eigenvalues of motor system matrix and $j$ represents imaginary unit, $\varphi$ initial phase, under suffix "rat" rating value of a motor. From (6), it is noted that the pulse has a value only when $\omega_n \neq \omega_{n-1}$, and it has no values during steady state. Thus only the sinusoidal voltage (5) is chosen as a control input during the steady state. Equation (5) and (6) imply a calculation of eigenvalues $-\boldsymbol{\tau}_i$. However, it is not necessary to calculate them separately, but to compute only the product and sum of these two eigenvalues. Hence, they are described such as the following equations:

$$\boldsymbol{\tau}_1\boldsymbol{\tau}_2 = (R_1R_2 - jR_1L_2\dot{\theta}_{en})/\sigma^2 \tag{7a}$$

$$\boldsymbol{\tau}_1 + \boldsymbol{\tau}_2 = (R_1L_2 + R_2L_1)/\sigma^2 - j\dot{\theta}_{en} \tag{7b}$$

Even if motor speed is changed, the calculation of (7) can be very simply conducted without doing a division and a root square. It should be noted that voltage command $\boldsymbol{u}_n^*$ can be determined feedforwardly without any current feedback loops and sinusoidal voltage $\dot{\boldsymbol{u}}_n$ obtained separately even transient state. The block diagram of the quick torque control method is represented in Fig. 3.

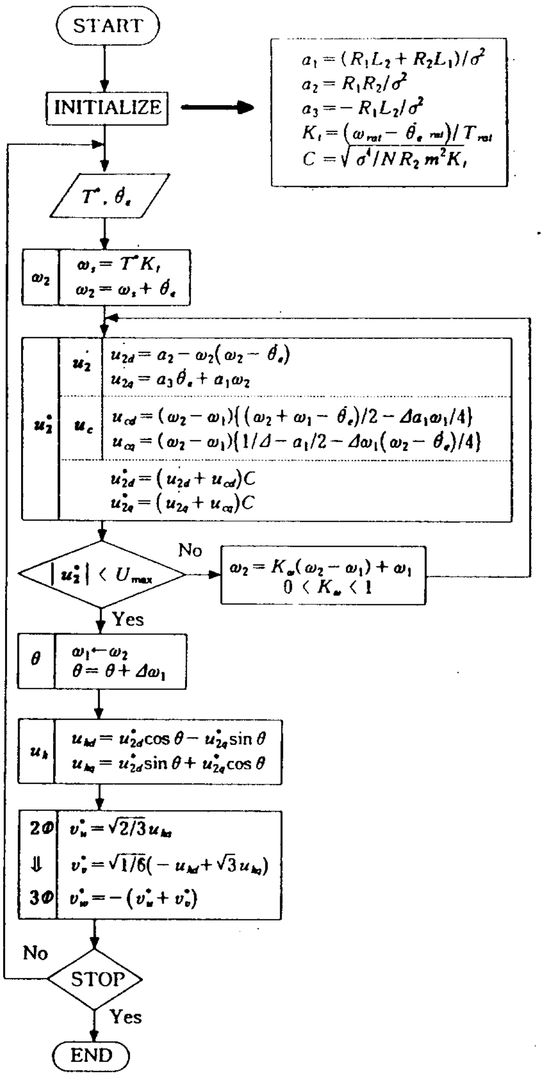



Fig. 3 Block diagram of the quick torque control method

## 3. The estimation of secondary resistance

In general, assuming that the stator current is $\boldsymbol{x}_1$, rotor current is $\boldsymbol{x}_2$ and input voltage is $\boldsymbol{u}$, the circuit equation of an I.M is described as follows:

$$\begin{bmatrix} \boldsymbol{u} \\ 0 \end{bmatrix} = \begin{bmatrix} R_1+L_1p & mp \\ m(p-j\dot{\theta}_e) & R_2+L_2(p-j\dot{\theta}_e) \end{bmatrix} \begin{bmatrix} \boldsymbol{x}_1 \\ \boldsymbol{x}_2 \end{bmatrix} \tag{8}$$

where $R_I$ is primary resistance and $L_i(i=1,2)$ is primary and secondary inductance, $p(=d/dt)$ differential operator. Current $\boldsymbol{x}_i$ is the same complex variable as $\boldsymbol{u}$ and these vectors are also represented in $d$-$q$ stationary reference frame.

As the primary current is moved from a steady state to another steady state during a small finite settling time of $\Delta$ and obtained sinusoidal voltage command even transient state, the differential operator $p$ in (8) can be replaced $j\omega$. Furthermore, equation (8) is divided two part $d$ and $q$ axis component as in equations (9) and (10).

$$u_d = R_1x_{1d} - L_1\omega x_{1q} - m\omega x_{2q} \tag{9a}$$

$$u_q = L_1\omega x_{1d} + R_1x_{1q} + m\omega x_{2d} \tag{9b}$$

$$0 = -m(\omega - \dot{\theta}_e)x_{1q} + R_2x_{2d} - L_2(\omega - \dot{\theta}_e)x_{2q} \tag{10a}$$

$$0 = m(\omega - \dot{\theta}_e)x_{1d} + L_2(\omega - \dot{\theta}_e)x_{2d} + R_2x_{2q} \tag{10b}$$

From these equations, parameters of $u_d$ and $u_q$ are known values from microprocessor of inverter, and $x_{1d}$, $x_{1q}$ can also be detected by current transformer installed to inverter. If motor speed is constant for a sampling time, the unknown parameters are secondary current and secondary resistance in (10). The secondary current value can be replaced easily by known values from the equation of stator side (9) as follows:

$$x_{2d} = (-L_1\omega x_{1d} - R_1 x_{1q} + u_q)/m\omega \quad (11a)$$

$$x_{2q} = (R_1 x_{1d} - L_1\omega x_{1q} - u_d)/m\omega \quad (11b)$$

Thus the secondary resistance which we want to estimate can be derived simply by substituting (11) into (10).

$$b_1\hat{R}_2 = c_1 \quad (12a)$$

$$b_2\hat{R}_2 = c_2 \quad (12b)$$

where,

$$b_1 = u_d - R_1 x_{1d} + \omega L_1 x_{1q}$$

$$b_2 = u_q - R_1 x_{1q} - \omega L_1 x_{1d}$$

$$c_1 = (\omega - \dot{\theta}_e)(\omega m^2 x_{1d} + L_2 b_2)$$

$$c_2 = (\omega - \dot{\theta}_e)(\omega m^2 x_{1q} - L_2 b_1)$$

In the above equation (12), the symbol hat "^" is used to describe estimated value of the secondary resistance by the proposed method. Consequently, secondary resistance $\hat{R}_2$ can be obtained toward minimization of $Q$ which is summation of error square in (13).

$$Q = (b_1\hat{R}_2 - c_1)^2 + (b_2\hat{R}_2 - c_2)^2 \quad (13)$$

Since the value of $Q$ has the minimum at the condition of $dQ/d\hat{R}_2 = 0$, the secondary resistance $\hat{R}_2$ can be written as

$$\hat{R}_2 = \frac{b_1c_1 + b_2c_2}{b_1^2 + b_2^2} \quad (14)$$

From (14), it requires only one division except for multiplications and additions to estimate the secondary resistance. Therefore, the suggested $R_2$ identification method can be conducted very simply. If the denominator of (14) comes close to infinitly small value, the estimated $\hat{R}_2$ has infinite value. To get rid of instability of the torque control system due to the divergence of $\hat{R}_2$, weight $W$ is considered in this paper.

$$\hat{R}_2(k+1) = (W\hat{R}_2(k) + \hat{R}_2(k+1))/(W+1) \quad (15)$$

## 4. Numerical simulation

Fig.4 shows the outline of the assumed PWM inverter system in the numerical simulation to estimate $R_2$.

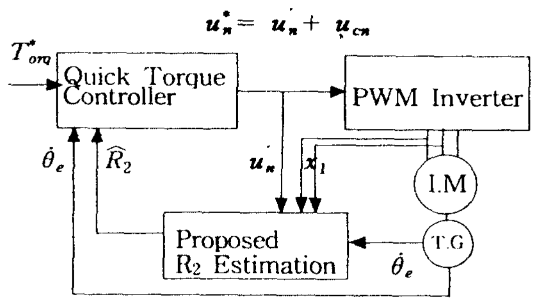



Fig. 4 The outline of the assumed PWM inverter system

The controller which is voltage source and voltage controlled inverter(VSI) system considered in the simulations has carrier frequency of 20kHz, three-phase, and 200V power source. Sampling period can be set appropriately so that the pulse voltage should be realized sufficiently in the VSI and it was set 1[ms] in this simulation. The tested machine is 4 poles, 2.2kW I.M and its parameters are shown in Table 1.

Fig. 5 Shows simulation flow chart.

Table 1 Parameters of the tested I.M

| | |
|---|---|
| 3-phase, 200V, 50Hz, 1260rpm | |
| $R_1$ : 0.58 Ω | $R_2$ : 0.06 Ω |
| $L_1$ : 100mH | $L_2$ : 108.8 mH |
| $m$ : 100.4 mH | |

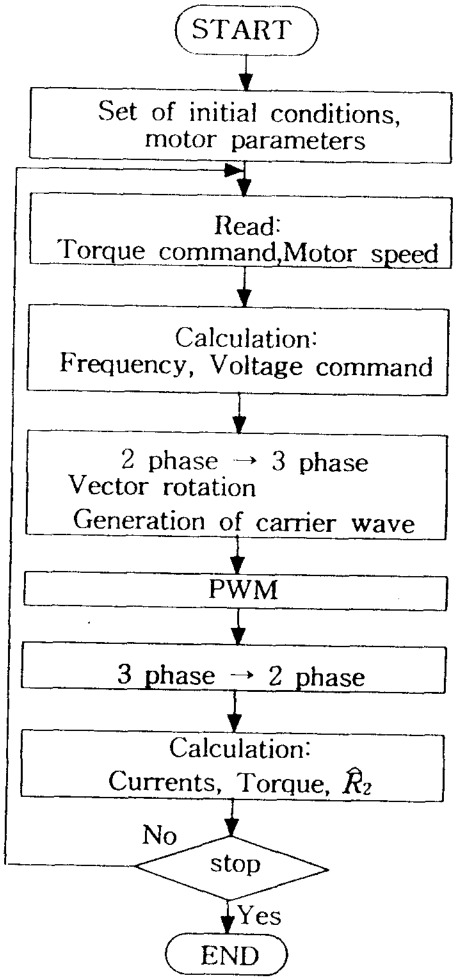
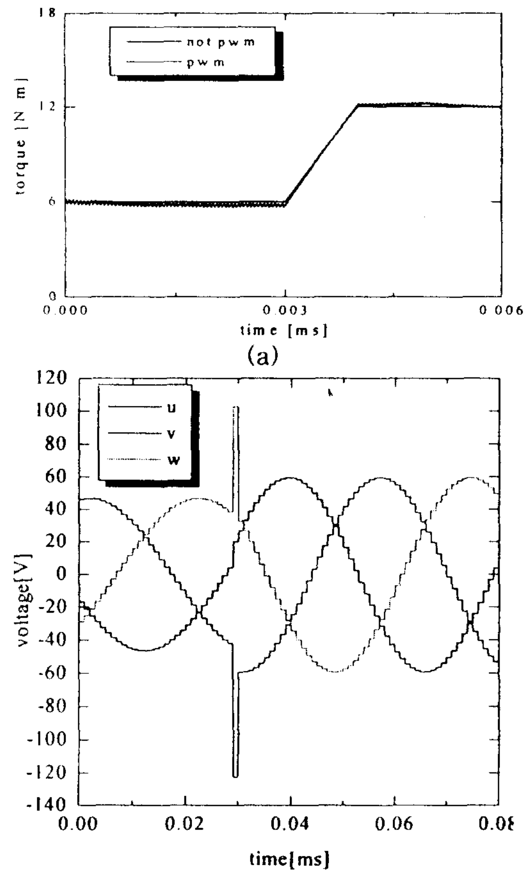



Fig. 5 Simulation flow chart

Fig. 6 shows torque reseponse and phase voltage command using the quick torque control method when torque reference is offered from 6[N.m] to 12[N.m] at motor speed 400[rpm].

In the numerical simulations, the current is calculated by the first approximation in the state equation of motors. Fig. 6(b) describes phase voltage variation under the step torque command. At the very time of torque change, pulse voltage is added on sinusoidal voltage to elliminate transient torque.

From this result, it can be seen that the stepwise torque response with settling time of 1[ms] is obtained and the pulse voltage is superimposed on sinusoidal voltage at the time point of torque change.




(b)

Fig. 6 Torque response and voltage command

Fig. 7 shows the effect of the secondary resistance variation. In this simulation, it is considered that $R_2$ is changed ±20% from real value after torque change.

Since the voltage command in (2) and (4) are dependent on the $R_2$, it is obvious that the variation of $R_2$ causes some steady state errors as shown in Fig. 7.

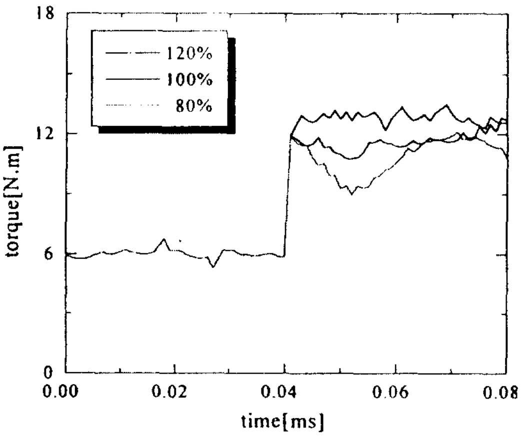



Fig. 7 The effect of secondary resistance variation

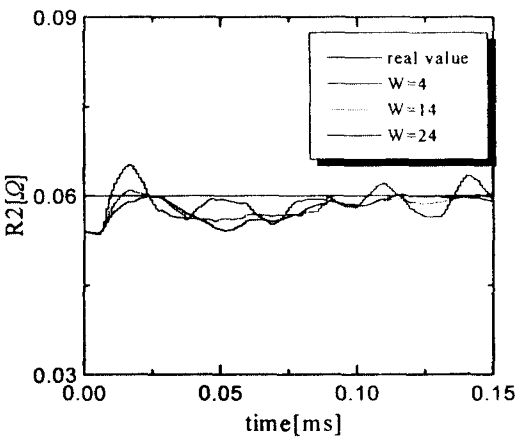



Fig. 8 The effect of weight W on the $R_2$ estimation

Fig. 8 indicates the effect of weight W on the $R_2$ estimation. From this results, it is seen that the estimated $\widehat{R}_2$ is fairly good approximation to real value without divergence by the proposed method.

Fig. 9 shows torque response using estimated $\widehat{R}_2$. In this case, the weight is taken as 14 and 24. This result indicates the torque response using the estimated $\widehat{R}_2$ has good agreement with torque command.

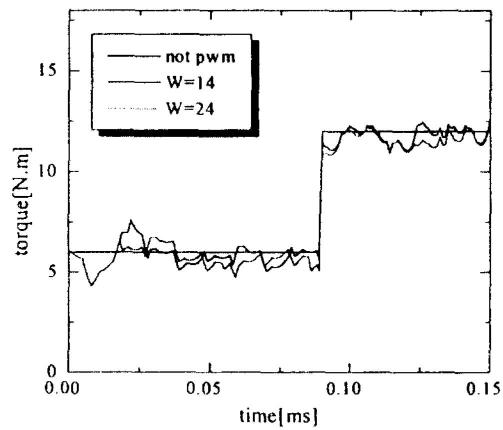



Fig. 9 Torque response using the estimated $\widehat{R}_2$

## 5. Conclusion

In this paper, a novel $R_2$ identification method is proposed for the quick torque control method to guarantee the high precision torque response. Through some numerical simulations, the validity of the proposed method confirmed successfully. The proposed method was derived theoretically from motor circuit equation using the features of the quick torque control method. Furthermore it can be conducted very simply by using primary voltage command and detecting primary currents at every sampling time. Therefore, it is expected to be applicable $R_2$ estimation of an I.M.

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