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A Modified Model Reference Adaptive System for the Speed Identification of Induction Motors

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Abstract— **The MRAS proposed by Schauder [8] is modified to improve robustness to the change of load torque and/or the variation of the stator resistance. The difference between the voltage and the current model is fed into the current model via proportional and integral gains. In order to generalize the MRAS, supposing that the rotor speed is time varying, we add a compensating term to the current model. It does not alter the Popov's integral inequality condition. Also, the asymptotic stability of the modified MRAS (MMRAS) is shown with the stability proof technique as in the original paper. By the simulation works, it is verified that the MMRAS obtains improved performance than the original MRAS.**

Keywords— **MRAS, Hyperstability, SPR, Robustness, Lyapunov equation.**

I. Introduction

In order to obtain fast dynamics of induction motor, field orientation control requires the rotor speed and/or position information. So, rotational transducers such as tachometer, resolver, and encoder need to be installed on the motor shaft. But, it leads to the problems of cabling, mounting, reliability, maintenance, size, cost, and ruggedness of induction motors [8]. Therefore, great advantages can be obtained without installation of rotational transducers.

Recently, in sensorless control area, numerous results [1-13] to obtain the rotor speed information of induction motors via advanced control theory have been reported. The most common method of identifying the rotor speed is to estimate the slip frequency and then to calculate the rotor speed as the difference between the electrical angular velocity and the slip frequency estimate. The papers [2][4][6][14] can be classified into this category. Unfortunately, the above schemes are faced with the problem of pure integration of induced voltages, which is extremely sensitive to the DC offset in the measurement data. Hence, recently proposed schemes on the identification of the rotor speed attempt to overcome this drawback. In [14], the effect of DC offset is minimized by subtracting the moving average value of rotor induced voltage from its integral value periodically. Using some kinds of model reference adaptive systems [7][8][10][12] are proposed. The pure integration is replaced by a low pass filter with error compensation [8]. On the other hand, some other authors [3][4][10][12][13] proposed adaptive observer schemes with parameter adaptation.

In this paper, we formulate the problem of identifying the rotor speed of induction motors in the presence of parameter mismatch. Specifically, the effect of the variation of the stator resistance on the MRAS are dealt with. Since the stator resistance is utilized in the voltage model, it is desirable to examine the effect of its variation on the MRAS.

In the following section, the MRAS is briefly reviewed. The voltage and the current models are used to estimate the rotor speed of induction motors. The voltage model produces the rotor flux λ_r^v by using the measurement data, the stator voltages and the stator currents. On the other hand, the other rotor flux λ_r^c from the current model is calculated. Since the current model contains the rotor speed, it is utilized as an adjustable model. The rotor speed in the current model is tuned via suitable adaptation mechanism such that the current model tracks the voltage model in a finite time interval.

Note that as the excitation frequency becomes lower, the computed rotor flux from the voltage model lesser accurate. That is to say, the effect of stator resistance variation is more serious at low speed than at high speed. Due to the inaccuracy of the voltage model at low speed, the performance of the MRAS is deteriorated and thus an alternative method is required.

Therefore, the MRAS proposed by Schauder [8] is modified to improve robustness to the change of load torque and/or the variation of the stator resistance. The difference between the voltage and the current model is fed into the current model via proportional and integral gains. In order to generalize the MRAS, the rotor speed is considered to be a time varying parameter in this paper. A compensating term for the time varying rotor speed is added to the current model. However, it does not alter the Popov's integral inequality condition. Also, the asymptotic stability of the MMRAS is shown with the stability proof technique as in the original paper. By the simulation works, it is verified that the MMRAS obtains improved performance than the original MRAS.

II. Mathematical Model of Induction Machines

Choosing the stator current and the rotor flux as a state vector in the stationary reference frame, we can describe the dynamic model of a squirrel cage induction motor as follows:

$$
\begin{aligned}
p.x &= Ax + Bu, \qquad (1)\\
A &= \begin{bmatrix} a_{11} & 0 & a_{13} & a_{14} \\ 0 & a_{11} & -a_{14} & a_{13} \\ a_{31} & 0 & a_{33} & a_{34} \\ 0 & a_{31} & -a_{34} & a_{33} \end{bmatrix}, \quad p. = \frac{d}{dt},\\
B &= \begin{bmatrix} b_1 & 0 \\ 0 & b_1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, x = \begin{bmatrix} i^s_{ds} \\ i^s_{qs} \\ \lambda^s_{dr} \\ \lambda^s_{qr} \end{bmatrix}, u = \begin{bmatrix} v^s_{ds} \\ v^s_{qs} \end{bmatrix},\\
a_{11} &= -\frac{R_s}{\sigma L_s} - \frac{L_m^2}{\sigma L_s L_r T_r}, a_{13} = \frac{L_m}{\sigma L_s L_r T_r},\\
a_{14} &= \omega_r \frac{L_m}{\sigma L_s L_r}, a_{31} = \frac{L_m}{T_r}, a_{33} = -\frac{1}{T_r},\\
a_{34} &= -\omega_r, \quad b_1 = \frac{1}{\sigma L_s}, \quad \sigma = 1 - \frac{L_m^2}{L_s L_r}.
\end{aligned}
$$

where i^s_{ds} and i^s_{qs} represent the stator d phase and q phase current, and λ^s_{dr} and λ^s_{qr} denote the rotor d phase flux and q phase flux, respectively. We denote by $L_s(L_r)$, L_m, $R_s(R_r)$ and $T_r = L_r/R_r$ the stator(rotor) self inductance, the mutual inductance, the stator(rotor) resistance, the rotor time constant. The total leakage coefficient is denoted by σ and the electrical rotor(slip) speed is denoted by $\omega_r(\omega_{sl} = \omega_e - \omega_r)$.

III. A Robustness Improved MRAS

The stator resistance varies over wide range due to the temperature change of induction motors. It is well known that inaccurate stator resistance affects flux estimate resulted from the voltage model. The original MRAS is affected by the variation of the stator resistance. When the stator resistance changes to 300 % from the nominal value, the performance of the MRAS is not satisfactory. Also, estimation result becomes poor when a sudden load torque is applied. Although high adaptation gains are used, steady state error still remains in the speed estimate and oscillatory behavior due to parameter mismatch takes place in the speed estimate. Therefore, it is desirable to modify the original MRAS such that the modified MRAS becomes more robust to the variation of the motor parameter and a sudden load torque change. In high speed range, its effect becomes negligible. However, as the speed becomes lower, the effect is dominant and thus it has to be compensated via suitable method. So, a compensation scheme are proposed by modifying the existent MRAS [8]. In this section, a modified MRAS for the time varying rotor speed is developed and stability analysis is done based on the Popov's hyperstability theory. In the following, λ^v_r and λ^c_r represent the rotor flux vectors produced from the voltage and the current model, respectively.

A. *Original MRAS*

- Voltage model :

$$p.\lambda^v_r = \frac{L_r}{M}(v_s - (R_s + \sigma L_s p.)i_s). \qquad (2)$$

- Current model :

$$p.\lambda^c_r = (-\frac{1}{T_r}I + \hat{\omega}_r J)\lambda^c_r + \frac{M}{T_r}i_s. \qquad (3)$$

where I and J are defined as

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}. \qquad (4)$$

- Error model :

$$
\begin{aligned}
p.[e] &= (-\frac{1}{T_r}I + \omega_r J)[e] - \Delta\omega_r J \lambda^c_r \\
&= F[e] - \Delta\omega_r J \lambda^c_r \qquad (5)
\end{aligned}
$$

where $[e] = \lambda^v_r - \lambda^c_r$, $\Delta\omega_r = \hat{\omega}_r - \omega_r$, and $F = -1/T_r I + J\omega_r$.

Due to the absence of the rotor speed in the voltage model, it is used as a target model. On the other hand, the current model is called an adjustable model. The rotor speed is updated via adaptation mechanism such that the current model tracks the voltage model in a finite time interval. The difference between two rotor flux models may be utilized an error signal. In the original paper, the cross product of the rotor fluxes produced from two models is used to tune the rotor speed. This speed update rule is found in the process of solving the Popov's hyperstability criterion (Popov's integral inequality). In other word, the rule must satisfy the following inequality criterion.

$$\int_0^{t_1} [e]^T \Delta\omega_r J \lambda^c_r dt \geq -\frac{\gamma^2}{2}, \quad \forall t_1 > 0. \qquad (6)$$

where γ is a positive real number.

For a strictly positive real system with a nonlinear time varying feedback loop, the Popov's hyperstability is applicable and useful.

The adaptive speed update law proposed in the original paper is described as follows :

$$\hat{\omega}_r = (K_p + \frac{K_I}{p.}) \cdot ([e]^T J \lambda^c_r) \qquad (7)$$

where λ^v_r and λ^c_r are two rotor flux vectors calculated from the voltage and the current models respectively. From the above equation, it can be stated that speed update is done such that the two rotor flux vectors becomes colinear. The difference of the magnitude of the two rotor flux vectors may not be important and thus the MRAS does not seriously affected by the variation of the mutual and the self inductance of rotor [8]. However, as stated in the previous section, the variation of the stator resistance and the change of load torque deteriorate the performance of the MRAS.

B. Modified MRAS

To obtain improved robustness to the variation of the stator resistance and the change of load torque, the current model in [8] is modified. As mentioned in the previous section, motor parameter mismatch and an applied load torque may cause bias and ripples in the rotor speed estimate. To cope with these problems, the difference between the voltage and the current model is fed into the current model via proportional and integral gains. It does not alter the Popov's integral inequality condition. Therefore, these corrective feedback terms may force the two rotor flux vectors of the voltage and the current models to be colinear irrespective of parameter mismatch and load torque change.

- Voltage model :

$$p.\lambda_r^v = \frac{L_r}{M}(v_s - (R_s + \sigma L_s p.)i_s). \qquad (8)$$

- Modified current model :

$$\begin{aligned} p.\lambda_r^c &= (-\frac{1}{T_r}I + \hat{\omega}_r J)\lambda_r^c + \frac{M}{T_r}i_s + K_\alpha[e] \\ &+ K_\beta \int_0^t [e]d\eta + \zeta sgn([e]^T J\lambda_r^c)J\lambda_r^c. \end{aligned} \qquad (9)$$

where the term $K_\alpha[e]$ moves the poles of error model to the left half complex plane and the integral term $K_\beta \int_0^t [e]d\eta$ is to take into account of the effect of parameter mismatch between model and plant. The last term is introduced to consider the time varying rotor speed. Here $\zeta = \max\{\omega_r(t)\}$ is the maximum rotor speed and $sgn(f)$ is defined as follows :

$$sgn(f) = \begin{cases} 1, & f \geq 0, \\ -1, & f < 0 \end{cases}. \qquad (10)$$

- Modified Error model :

$$\begin{aligned} p.[e] &= F[e] - \Delta\omega_r J\lambda_r^c - K_\alpha[e] \\ &- K_\beta \int_0^t [e]d\eta - \zeta sgn([e]^T J\lambda_r^c)J\lambda_r^c \\ &= F[e] - W_1 \qquad (11) \\ W_1 &= \Delta\omega_r J\lambda_r^c + K_\alpha[e] \\ &+ K_\beta \int_0^t [e]d\eta + \zeta sgn([e]^T J\lambda_r^c)J\lambda_r^c (12) \end{aligned}$$

where $[e] = \lambda_r^v - \lambda_r^c$ and $K_\alpha, K_\beta > 0$. Here $\Delta\omega_r = \hat{\omega}_r - \omega_r$.

In the following section, with the stability proof technique as in the original paper, a speed adaptive law for the modified MRAS is derived with useful Lemmas and the hyperstability theory for the time varying rotor speed case. The modified MRAS is more general than the original MRAS.

C. Derivation of Adaptive Law

For all $t_1 \geq 0$, to satisfy the Popov's integral inequality,

$$\int_0^{t_1} [e]^T W_1 dt \geq -\frac{\gamma^2}{2} \qquad (13)$$

the following speed update law is utilized.

$$\hat{\omega}_r = K_p[e]^T J\lambda_r^c + K_I \int_0^t [e]^T J\lambda_r^c d\tau. \qquad (14)$$

Note that the speed update law is identical to the one in the original paper. Although the same adaptive law is used in the MMRAS, the closed loop system is asymptotically hyperstable with respect to the hyperstability theory.

The objective of this section is to show that the selected speed update law as above satisfies the Popov's integral inequality criterion. That is, it is to show that the following integral inequality holds for the given speed update law.

$$\begin{aligned} &\int_0^{t_1} \left[\Delta\omega_r[e]^T J\lambda_r^c + K_\alpha[e]^T[e] + K_\beta[e]^T \int_0^t [e]d\eta\right] dt \\ &+ \int_0^{t_1} \zeta sgn([e]^T J\lambda_r^c)[e]^T J\lambda_r^c dt \geq -\frac{\gamma^2}{2}. \end{aligned} \qquad (15)$$

For later use, three Lemmas for integral inequality are stated as follows :

Lemma 1. *For all $k > 0$ and a differentiable function $f(t)$, the following integral inequality holds.*

$$\int_0^{t_1} k\,[p.f(t)]\,[f(t)]\,dt \geq -k\frac{\gamma_1^2}{2}, \quad \forall t_1 \geq 0. \qquad (16)$$

Lemma 2. *For all $K_\alpha, K_\beta > 0$ and an integrable 2×1 vector function $[e]$, the following integral inequality holds.*

$$\int_0^{t_1} \left[K_\alpha[e]^T[e] + K_\beta[e]^T \int_0^t [e]d\eta\right] dt \geq 0, \quad \forall t_1 \geq 0. \qquad (17)$$

Lemma 3. *For a given $\zeta = \max\{\omega_r(t)\}$ and for all $t_1 \geq 0$, the following inequality holds.*

$$\int_0^{t_1} (\zeta - \omega_r/sgn([e]^T J\lambda_r^c))sgn([e]^T J\lambda_r^c)[e]^T J\lambda_r^c dt \geq 0. \qquad (18)$$

Now, asymptotic stability for the modified model reference adaptive system can be stated as the following Theorem 1. Here, for an $n\times n$ symmetric matrix A, $A > 0$ implies A is a positive definite matrix. In other word, for an $n\times 1$ vector x, $x^T Ax > 0$ if $x \neq 0$. In this paper, the rotor speed is considered to be time varying, while the original paper assumes it a constant. When the rotor speed is time varying, the strictly positive real condition for the transfer matrix $G(s) = (sI - F)^{-1}$ becomes useless. Therefore, the strictly positive real condition for $G(s)$ must be replaced by the Lyapunov equation i.e., $\dot{P}(t) + F^T(t)P(t) + P(t)F(t) = -Q(t)$. Here $P(t), Q(t)$ are symmetric positive definite matrices.

Theorem 1. *The modified MRAS (8),(9) or (11) is asymptotically hyperstable if the following conditions are satisfied.*

(a) There exist symmetric positive definite matrices $P(t), Q(t)$ such that the Lyapunov equation $\dot{P}(t) + F^T P(t) + P(t)F = -Q(t)$ is satisfied.

(b) $\hat{\omega}_r = K_p[e]^T J\lambda_r^c + K_I \int_0^t [e]^T J\lambda_r^c d\tau.$

(c) $\zeta = \max\{\omega_r(t)\}.$

Proof: In the original paper, the condition (a) in Theorem 1 is described as the strictly positive real condition for the transfer matrix $G(s)$ with the rotor speed constant. It is checked by the positive definite property of $G(j\omega) + G^*(j\omega)$ for all ω. Here, $*$ denotes the complex conjugation. However, in this case, since the rotor speed is time varying, it must be checked by the existence of symmetric positive definite matrices $P(t)$ and $Q(t)$ such that the Lyapunov equation $\dot{P}(t) + F^T(t)P(t) + P(t)F(t) = -Q(t)$ is satisfied.

Choosing $P(t) = \kappa I, \kappa > 0$, we know that $\exists Q(t) = Q^T(t) > 0$. It follows that

$$Q(t) = -\kappa\left(F^T(t) + F(t)\right) = \kappa \begin{bmatrix} 2/T_r & 0 \\ 0 & 2/T_r \end{bmatrix} > 0. \tag{19}$$

Therefore, the condition (a) in Theorem 1 is easily checked.

It remains to show that the Popov's integral inequality criterion holds with the condition (b) and (c) in Theorem 1. That is, it suffices to prove that

$$\int_0^{t_1} \left[\Delta\omega_r[e]^T J\lambda_r^c + K_\alpha[e]^T[e] + K_\beta[e]^T \int_0^t [e]d\eta\right] dt + \int_0^{t_1} \zeta sgn([e]^T J\lambda_r^c)[e]^T J\lambda_r^c dt \geq -\frac{\gamma^2}{2}. \tag{20}$$

With condition (b) and (c), Lemma 1, Lemma 2, and Lemma 3, the above inequality can be easily verified as follows :

$$\begin{aligned} W &\equiv \int_0^{t_1} [e]^T W_1 dt \\ &= \int_0^{t_1} \hat{\omega}_r[e]^T J\lambda_r^c dt \\ &\quad + \int_0^{t_1} \left[K_\alpha[e]^T[e] + K_\beta[e]^T \int_0^t [e]d\eta\right] dt \\ &\quad + \int_0^{t_1} (\zeta - \omega_r/sgn([e]^T J\lambda_r^c))sgn([e]^T J\lambda_r^c)[e]^T J\lambda_r^c dt \\ &\geq \int_0^{t_1} \hat{\omega}_r[e]^T J\lambda_r^c dt \\ &\quad + \int_0^{t_1} (\zeta - \omega_r/sgn([e]^T J\lambda_r^c))[e]^T J\lambda_r^c dt \\ &\geq \int_0^{t_1} \hat{\omega}_r[e]^T J\lambda_r^c dt \\ &\geq -\frac{\gamma^2}{2}. \end{aligned} \tag{21}$$

In the above, the last inequality is proved in the original paper with the same speed adaptive law. Therefore the modified MRAS is asymptotically hyperstable, although the rotor speed is time varying. ∎

D. Robustness to the Stator Resistance

With the exact stator resistance, the performance of the two schemes, MRAS and MMRAS is almost identical. However, the variation of the stator resistance and/or the change of load torque deteriorate the performance of MRAS. However, the MMRAS is more robust than the MRAS to the variation of the stator resistance and load torque. The stator resistance depending on machine temperature varies over wide range. So, in order to study the effect of the stator resistance on the rotor speed estimate, it is assumed that the stator resistance is perturbed by ΔR_s from the nominal value R_s. For a perturbed stator resistance $R_s + \Delta R_s$, we obtain a perturbed error equation for MRAS as follows.

$$\begin{aligned} p.[e] &= F[e] - \Delta\omega_r J\lambda_r^c - \Delta R_s \frac{L_r}{M} i_s \\ &= F[e] - \Delta\omega_r J\lambda_r^c - \Delta\epsilon_1 \end{aligned} \tag{22}$$

where $\Delta\epsilon_1 = \Delta R_s \frac{L_r}{M} i_s$.

On the other hand, for the modified MRAS, we obtain the following error equation.

$$\begin{aligned} p.[e] &= F[e] - \Delta\omega_r J\lambda_r^c - K_\alpha[e] - K_\beta \int_0^t [e]d\eta \\ &\quad - \zeta sgn([e]^T J\lambda_r^c)J\lambda_r^c - \Delta\epsilon_1. \end{aligned} \tag{23}$$

The effect of K_α and K_β inserted in the modified MRAS on the Popov's integral inequality can be stated as follows. In the presence of motor parameter mismatch, the Popov's integral inequality condition may not be satisfied in the original MRAS. But, for the MMRAS, the possibility to satisfy the Popov's integral inequality is larger than the MRAS due to the additional feedback terms. To compare the robustness of the two schemes to the variation of the stator resistance, the following notations are introduced.

Notation.

$$\begin{aligned} Q_1 &= \Delta R_s \frac{L_r}{M} \int_0^{t_1} [e]^T i_s dt, \\ Q_2 &= \int_0^{t_1} \left[K_\alpha[e]^T[e] + K_\beta[e]^T \int_0^t [e]d\eta\right] dt \\ &+ \Delta R_s \frac{L_r}{M} \int_0^{t_1} [e]^T i_s dt. \end{aligned} \tag{24}$$

The above Q_1 denotes the degree to which the Popov's integral inequality holds with respect to the stator resistance change. In other words, it may be called a *robustness factor* (degree) to the change of the stator resistance. With this concept, it is shown that the modified MRAS has improved robustness factor Q_2 than the original MRAS. It follows by the following inequality that by Lemma 2

$$\begin{aligned} Q_2 - Q_1 &= \int_0^{t_1} \left[K_\alpha [e]^T [e] + K_\beta [e]^T \int_0^t [e] d\eta \right] dt \\ &\geq 0, \quad \forall t_1 > 0. \end{aligned} \tag{25}$$

Since $Q_2 \geq Q_1$, it can be said that the modified MRAS is more robust than the original MRAS to the variation of the stator resistance.

IV. Simulation Results

In order to evaluate the performance of the modified MRAS with respect to the variation of the stator resistance and the change of load torque, computer simulation works are done for the two MRAS schemes.

A. *Robustness at* 3 *Hz and* 30 *Hz operations*

It is assumed that the stator resistance is perturbed to 300 % from its nominal value at $t = 3$. First simulation is to test the low speed operation at 3 Hz(90 rpm). Test for the high speed operation with 30 Hz (900 rpm) is done in second simulation. Fig. 1 shows the plot of the rotor speed estimate at 3 Hz along with its error and two rotor fluxe vectors of voltage and current models. When the stator resistance is changed, the results are depicted in Fig. 2. As shown in Fig. 2, the estimation results for the 300 % perturbed stator resistance is very poor. At $t = 3$ seconds, oscillatory behavior occurs in the speed estimate and steady state error exists. However, the modified MRAS reduces the settling time of oscillation and the magnitude of steady state error. The improved estimation results of the modified MRAS are shown in Fig. 3.

Second simulations are to test the high speed operation at 30 Hz with the same condition as first simulation except the load torque change to 20 Nm. Fig. 4, Fig. 5, and Fig. 6 show the simulation results for these cases. When the load torque is applied and the stator resistance is changed at the high speed, note that the responses of the modified MRAS to the variation of the stator resistance are also better than that of original one.

By these simulation works, the superiority of the modified MRAS are verified with respect to the magnitude of speed ripples in the rotor speed estimate, steady state error, and convergence time under the situation that a load torque is applied and the stator resistance is changed.

V. Conclusion

A modified MRAS so as to identify the rotor speed was proposed. The proposed MMRAS obtained improved *robustness factor* to the variation of the stator resistance. The difference between the voltage and the current models was fed into the current model via proportional and integral gains to improve the performance of the original MRAS. The MMRAS could be applied to identify the time varying rotor speed. The asymptotic stability of the MMRAS was shown with the hyperstability theory. By the simulation works, the superiority of the modified MRAS to the original MRAS was verified by the robustness to the variation of the stator resistance and the change of load torque.

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