《高阶会员专属视频》-第17期

IEEE论文导读：增加霍尔元件分辨率的第二种方法，更简单的算法，应用在BLDC速度控制系统！

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Model Reference Adaptive Control-Based Speed Control of Brushless DC Motors With Low-Resolution Hall-Effect Sensors

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Abstract—**A control system with a novel speed estimation approach based on model reference adaptive control (MRAC) is presented for low cost brushless dc motor drives with low-resolution hall sensors. The back EMF is usually used to estimate speed. But the estimation result is not accurate enough at low speeds because of the divided voltage of stator resistors and too small back EMF. Moreover, the stator resistor is always varying with the motor's temperature. A speed estimation algorithm based on MRAC was proposed to correct the speed error estimated by using back EMF. The proposed algorithm's most innovative feature is its adaptability to the entire speed range including low speeds and high speeds and temperature and different motors do not affect the accuracy of the estimation result. The effectiveness of the algorithm was verified through simulations and experiments.**

Index Terms—**Brushless dc motor, low-resolution hall sensor, model reference adaptive control, speed estimation.**

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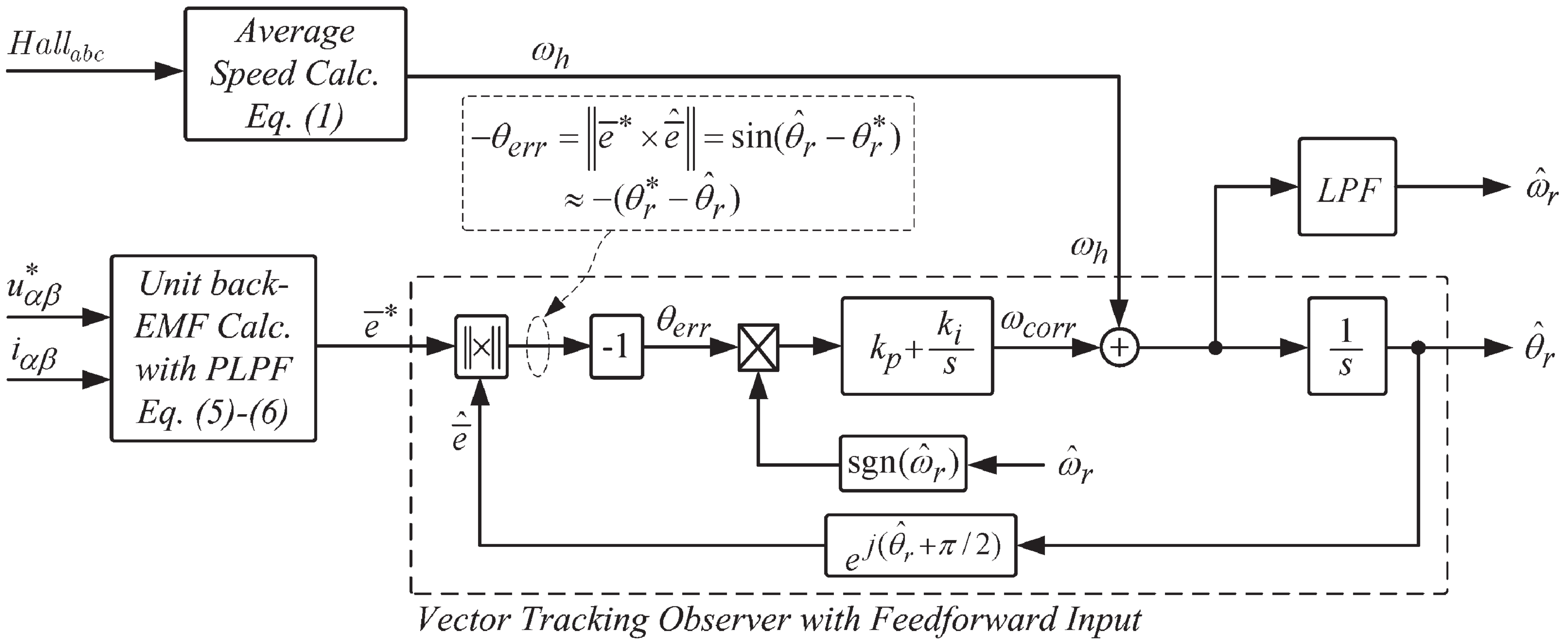

Fig. 4. Proposed vector-tracking position observer.

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I. Introduction

BRUSHLESS dc (BLDC) motors usually use three or more Hall sensors to obtain rotor position and speed measurement. It would be necessary to inverse the time difference between two successive Hall sensor signals to obtain reliable speed measurement. Notice that there are only a few sensor signals available to the motor at low speeds. There may be 12 or 24 sensor pulses per round which depend on the number of poles. The sampling time, thus, becomes a variable according to the motor speed. These systems have uncertainty in a discrete time model and have a lot of difficulties to design speed regulators. Moreover, the sampling time is too long for speed regulations at low speeds.

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For BLDC motors, the most popular speed estimation method may be based on back EMF. Operation rotor speeds determine the magnitude of the back EMF. At low speeds, the back EMF is not large enough to estimate the speed and position due to inverter and parameter nonlinearities. This paper presents a MRAC speed estimation algorithm by using the back EMF. The proposed algorithm can compensate the voltage occupied by the stator resistor adaptively at low speeds and is valid over the entire speed range. Moreover, the parameters of the algorithm can be commonly used for different BLDC motors.

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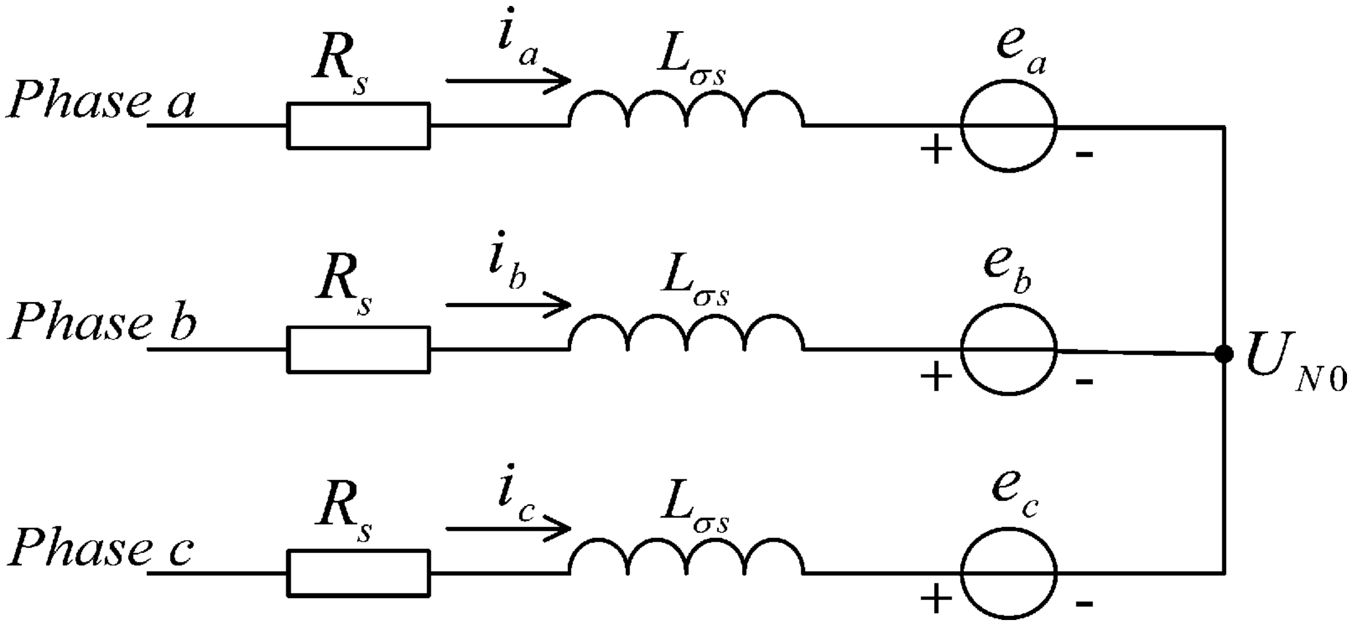

Fig. 1. Equivalent circuit of a star connection BLDC motor.

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with phase variables is

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_{\sigma s} & 0 & 0 \\ 0 & L_{\sigma s} & 0 \\ 0 & 0 & L_{\sigma s} \end{bmatrix} \times \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} + \begin{bmatrix} U_{N0} \\ U_{N0} \\ U_{N0} \end{bmatrix} \tag{1}$$

and the electromagnetic torque equation is

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \tag{2}$$

where u_a, u_b, and u_c are the terminal phase voltages with respect to the power ground, R_s is the stator resistance of phase windings, i_a, i_b, and i_c are phase current, $L_{\sigma s} = L_s - L_m$ is the equivalent inductance of phase windings, L_s and L_m are self-inductance and mutual inductance, respectively, e_a, e_b, and e_c are trapezoidal back EMFs, U_{N0} is the neutral point to ground voltage, and ω_m is the speed of the rotor.As a BLDC motor, there are only two phases which have current at the same time. For

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are only two phases which have current at the same time. For this analysis, the current from phase a to phase b is considered. There are following equations:

$$\begin{cases} i_a = -i_b \\ i_c = 0 \\ e_a = -e_b \\ T_e = \dfrac{2e_a i_a}{\omega_m} \end{cases} \tag{3}$$

and the line voltage between phase a and phase b is

$$u_{ab} = u_a - u_b = 2R_s i_a + 2L_{\sigma s}\frac{di_a}{dt} + 2e_a\,. \tag{4}$$

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Because the rotor of a BLDC motor is permanent magnet, the back EMFs are proportional to the electric speed of the rotor

$$e_a = -e_b = k_e \omega_r \tag{5}$$

where k_e is back EMF coefficient and is a constant. According to (4) and (5), the speed of the rotor can be given as

$$\omega_m = \frac{u_{ab} - 2R_s i_a - 2L_{\sigma s} \frac{di_a}{dt}}{pk_e} \tag{6}$$

and $\omega_r = p\omega_m/2$, where p is the number of poles of a motor.

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In stable condition or when i_a is changed very slowly $di_a/dt \approx 0$. Then, (6) can be rewritten as

$$\omega_m = \frac{u_{ab} - 2R_s i_a}{pk_e}. \tag{7}$$

B. Speed Estimation

Referring to (7), the speed of the rotor can be calculated by voltage and current without Hall sensors. The line voltage u_{ab} can be estimated by pulse width modulation (PWM) signals. The phase current i_a can be sensed from hardware. R_s is a parameter of the motor and is proportional to the temperature. If the change of R_s is neglected, the estimated speed is very accurate especially at high speed but when a motor is working at low speed, the estimated speed is not accurate enough. It is mainly because the back EMF is too small comparing with$R_s i_a$. A small error of u_{ab} or $R_s i_a$ would lead to an inaccuracy of the estimated speed.

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p and k_e in (7) are constant for a known BLDC motor. But they are changed with different BLDC motors. Actually, p is usually on the plate of a motor and can be obtained easily. k_e, however, is seldom on the plate.

Thus, there are two problems with the speed estimation based on the back EMF of BLDC motors. 1) The accuracy of the estimated speed is not enough at low speed and 2) R_s is not constant. It is varying by temperature. p and k_e are variables for different motors. Therefore, the algorithm based on (7) cannot be commonly used for different motors or in different conditions for the same motor.

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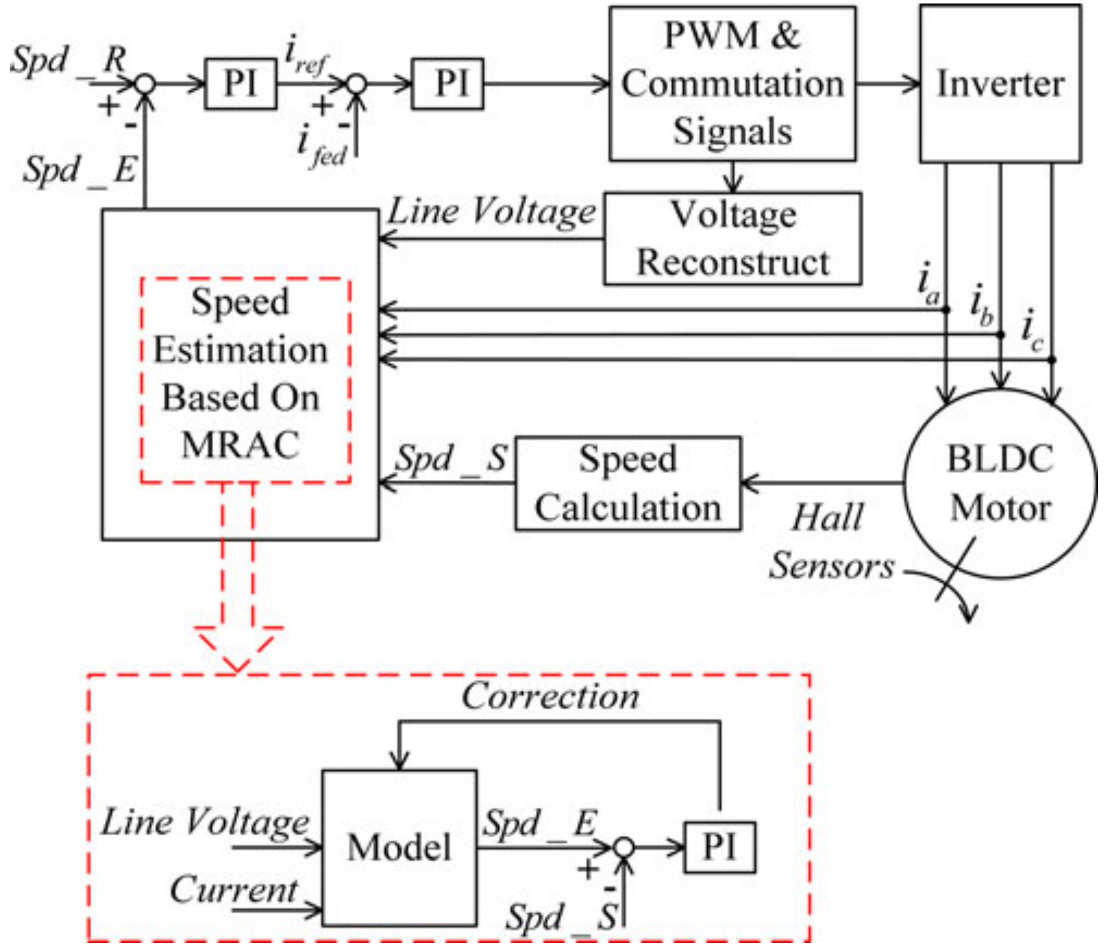

Fig. 2. Block diagram of the system.

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$$\omega_m = \frac{u_{ab} - 2R_s i_a}{pk_e}. \qquad (7)$$

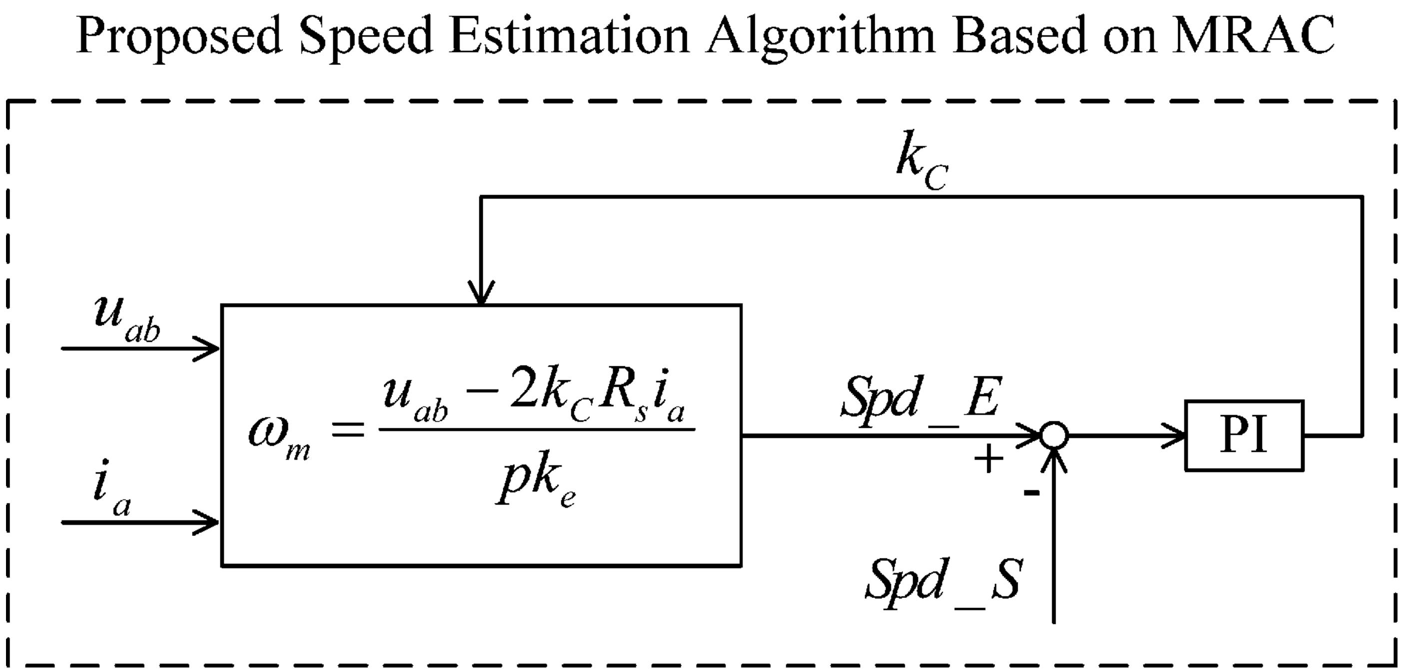

Fig. 3. Speed estimation algorithm considering the voltage compensation of the stator resistor.

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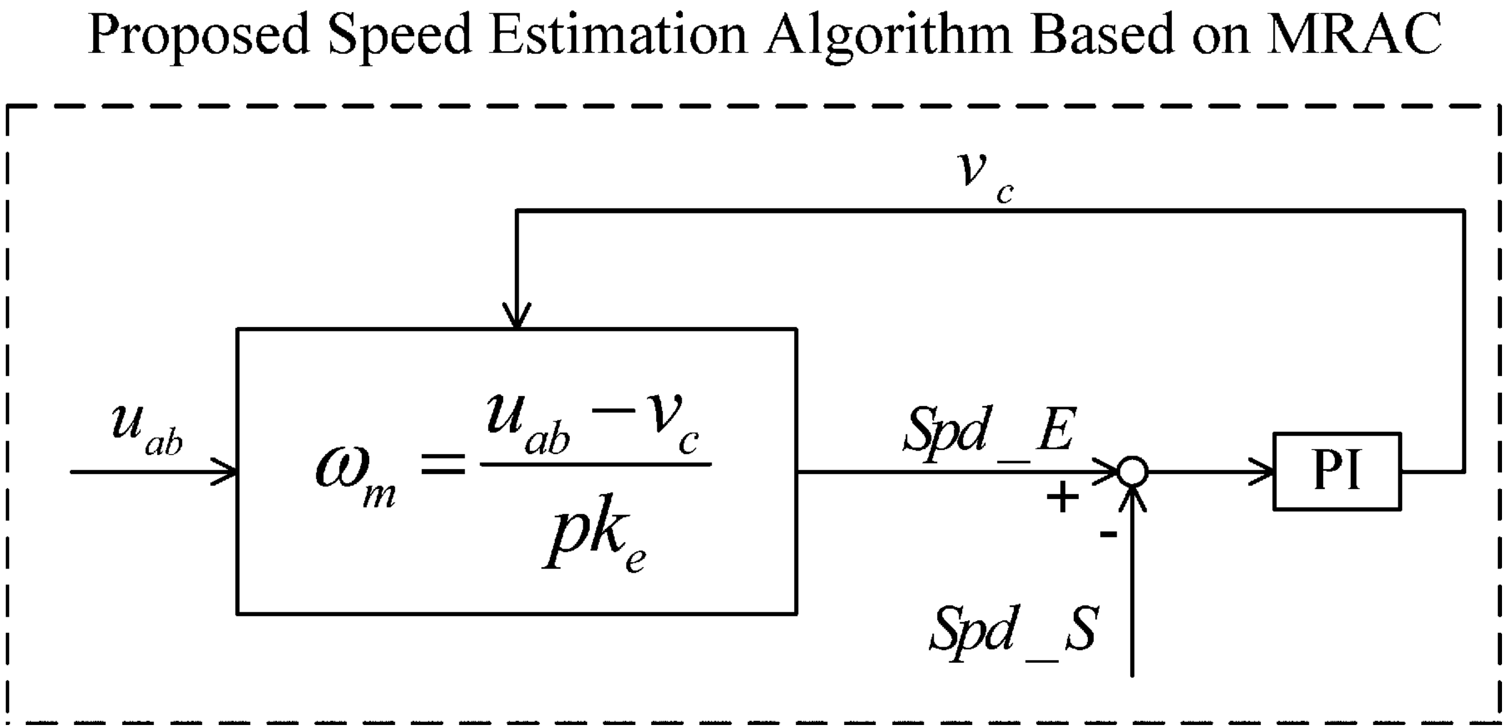

Fig. 4. Approach to simplify algorithm.

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At high speed, the divided voltage of stator resistors can be neglected. The voltage on a motor is almost the back EMF. Then, referring to (7), an approach of the high speed estimated algorithm is proposed here

$$\omega_m = \frac{u_{ab}}{pk_e}. \tag{8}$$

According to (8), k_e produces great influence on the accuracy of the estimated result at high speeds. An approach of the high-speed estimated algorithm was proposed based on Fig. 4. The block diagram is shown in Fig. 5. k_{e0} is the initial value of k_e and $k_e = k_{e0}k_C$. If k_{e0} is not accurate, the PI regulator will change the value of k_c until *Spd_E* equals to *Spd_S*. In this way, the error of the estimated speed caused by the inaccuracy of k_e is corrected by k_c.

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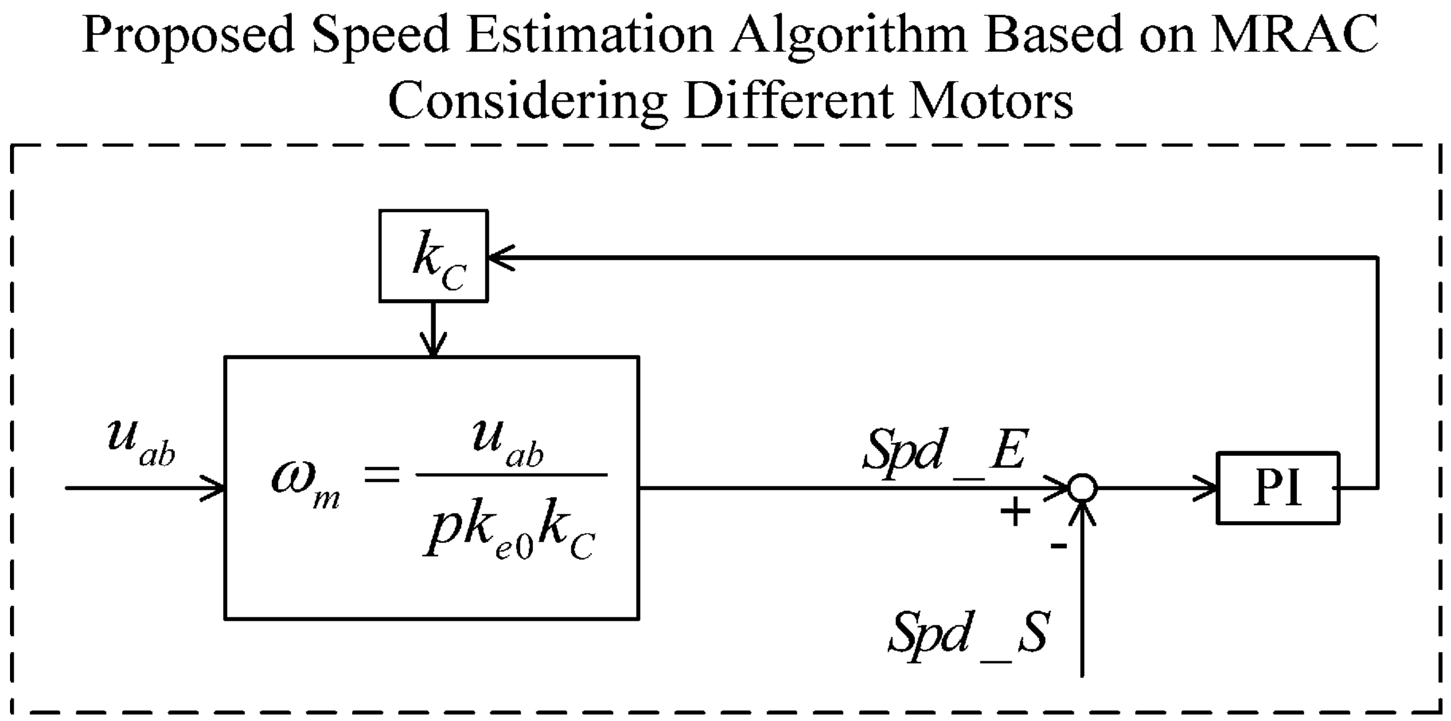

Fig. 5. Estimation algorithm approach considering different motors at high speed.

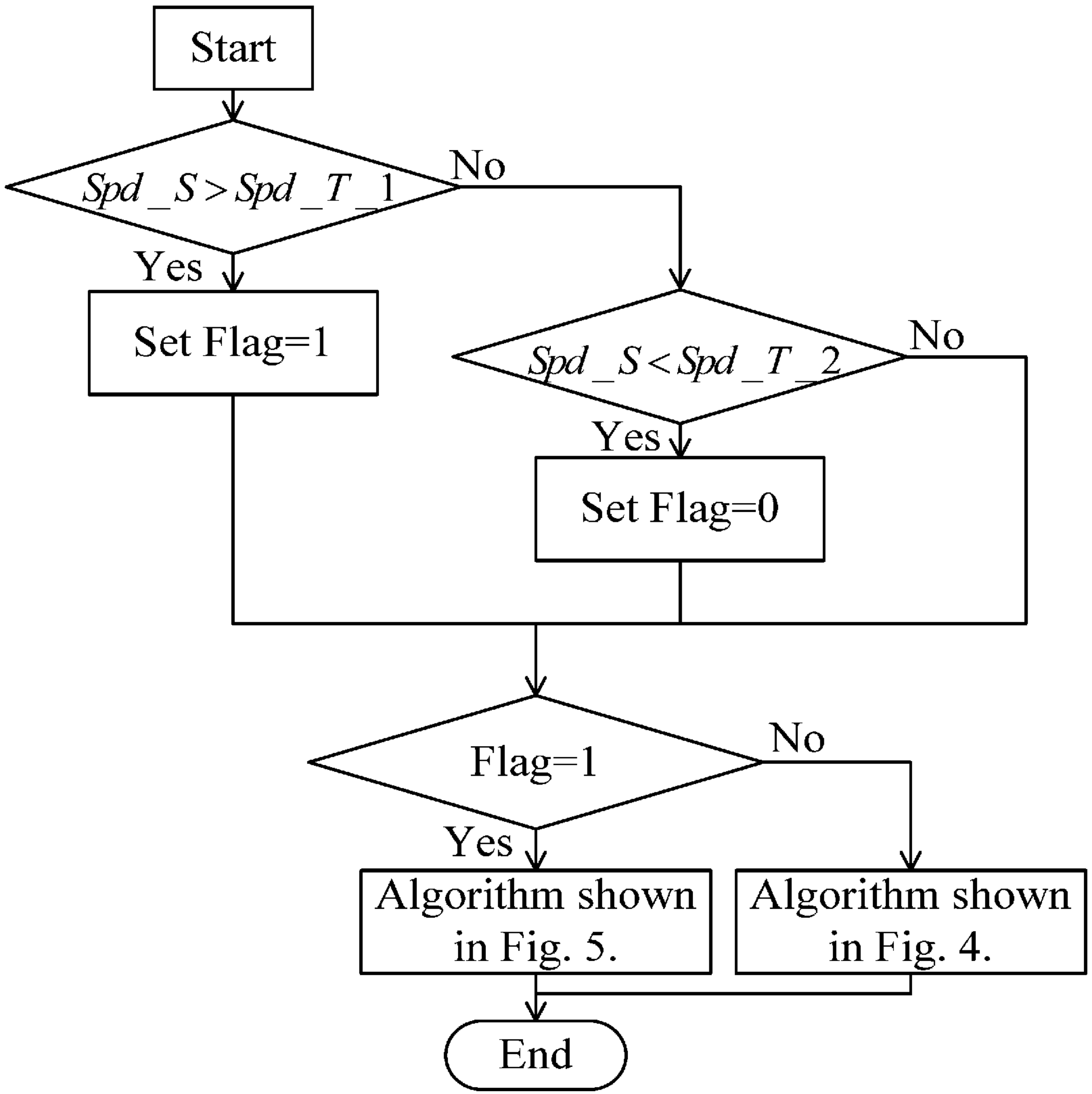

Fig. 6. Flow chart of estimation algorithm.