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.**

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.

In order to make BLDC motors with low-resolution encoders work at very low speed and reduce the difficulty of speed regulators' design, several methods have been developed to obtain high accurate speed measurement. These methods are commonly addressed as estimation methods. Instantaneous speed estimation based on a reduced-order disturbance torque observer provides the merits of simple structure and easy implementation [1]. But the high gain problem occurs in real application for mechanical noise and oscillation of system. In [2], a reduced-order extended Luenberger observer was proposed to reduce the sensitivity to the instantaneous speed estimation by the variation of the inertia moment. A computationally intensive Kalman filter is successfully used in dealing with velocity transients [3], but it is susceptible to the mismatch of parameters between the filter's model and the motor. In [4], a dual observer was proposed. The dual observer can estimate the rotor speed and position without time delay or bumps. All the observer-based methods share the feature of providing high accuracy of the speed estimation with satisfactory dynamic performance. But they suffer from the dependence on system parameters and need heavy computation [5]. A model free enhanced differentiator is proposed for improving velocity estimation at low speed [6], [7]. But the computation includes the fractional power of variables. Many other authors have suggested that accurate speed estimation can be obtained by using a low-resolution encoder, together with a position extrapolation algorithm, implemented in the drive control processor [8]–[12]. However, the estimation in [12] was dependent on the accuracy of position sensor and mechanical parameters. Hardware approaches involving a phase locked loop [13], [14] are feasible for a drive running at near-constant velocity, but may be unable to deal with transient velocity operation.

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.

II. Description of Estimation Algorithm

A. Model of BLDC Motors

The equivalent circuit of a Y-connection BLDC motor is shown in Fig. 1 [15].

A BLDC motor has three stator windings and permanent magnets on the rotor. Its voltage equation of three windings

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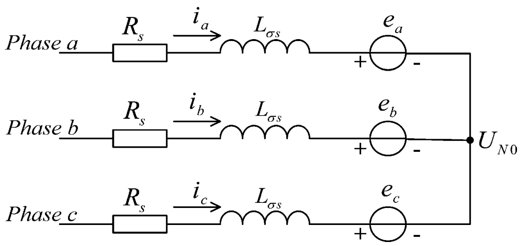


Fig. 1. Equivalent circuit of a star connection BLDC motor.

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 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

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

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.

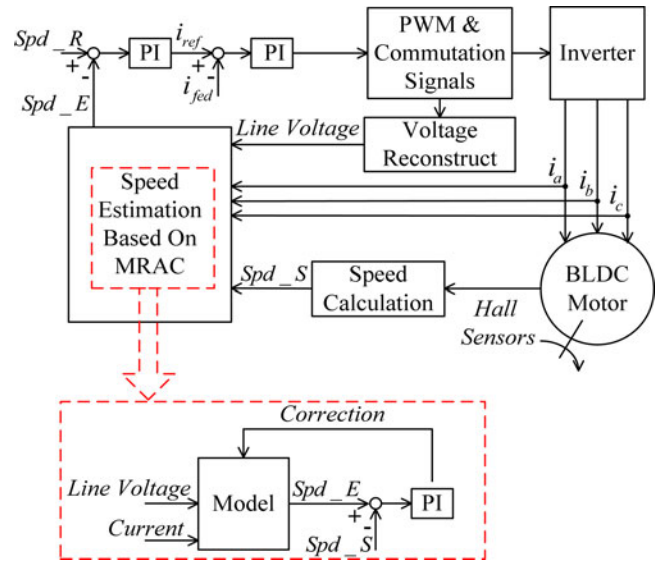


Fig. 2. Block diagram of the system.

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.

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.

C. Basic Idea

To solve the two problems mentioned above, a speed estimation algorithm based on MRAC was proposed. Fig. 2 shows the block diagram of the speed control system with the proposed speed estimation algorithm. It consists of a power circuit and control circuits which perform following functions: PWM

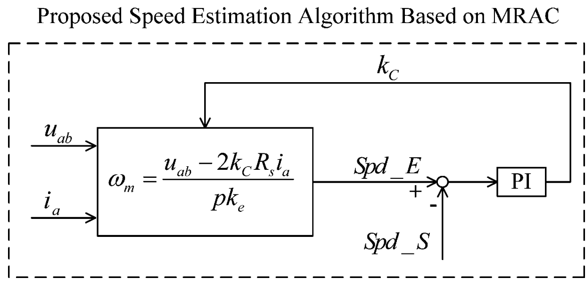


Fig. 3. Speed estimation algorithm considering the voltage compensation of the stator resistor.

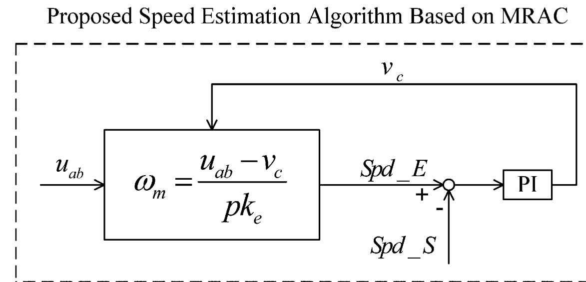


Fig. 4. Approach to simplify algorithm.

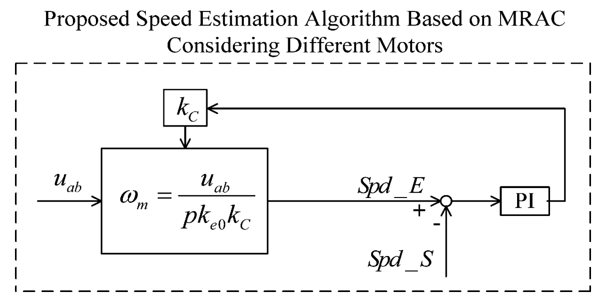


Fig. 5. Estimation algorithm approach considering different motors at high speed.

strategy, current control, current commutation, speed estimation, and speed control.

The main blocks of the speed estimation is a MRAC-based regulator. The speed estimated by the back EMF and the speed calculated by Hall sensors are the inputs of the regulator. The output of the regulator is a correction variable for the estimated speed. *Spd_E* is the estimated speed. *Spd_S* is the calculated speed by Hall sensors. If *Spd_E* is not equal to *Spd_S*, a correction is given by the PI regulator and then, *Spd_E* is calculated again based on the proposed model. The reference current $i_{\rm ref}$ is changed by the speed regulator. Through the current regulator, the output voltage of the inverter is being tuned and *Spd_S* is changed. In this way, the PI regulator used in the estimation algorithm is always working until *Spd_E* equals to *Spd_S*.

III. Design of Estimation Algorithm Based on MRAC

For this analysis, the current from phase a to phase b is considered.

A. Speed Estimation Algorithm

The inaccuracy of the low speed estimation is mainly because of the divided voltage of the stator resistor. So an estimation algorithm considering the voltage compensation of the stator resistor is presented firstly. It is shown in Fig. 3. The estimated speed is calculated by using (7).

In Fig. 3, where R_s is not accurate or changed with the temperature, *Spd_E* will not be equal to *Spd_S*. Because k_c affects *Spd_E* and *Spd_E* is the input of the speed PI regulator, the speed PI regulator will change the output voltage to compensate divided voltage of the stator resistor adaptively. k_c is always tuning until *Spd_E* equals to *Spd_S*. Therefore, the control system including this proposed speed estimation algorithm can keep the accuracy of the estimated speed at very low speed.

The $2k_c R_s i_a$ not only needs the value of R_s but also needs the value of current. Actually the output of the PI regulator proposed in Fig. 3 can completely compensate the divided voltage of the stator resistor. Therefore, a simple algorithm is proposed in Fig. 4 the v_c is the output of the PI regulator and $2k_c R_s i_a$ is replaced by v_c.

B. Algorithm Approach Considering Different Motors

For different motors, the value of p and k_e may be changed. p could be easily obtained from the plate of a motor. However, k_e is seldom shown on the plate. Therefore, the initial value of k_e may be inaccuracy.

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.

C. Speed Estimation Algorithm Considering Voltage Compensation and Different Motors

At low speed, the primary reason of the estimated inaccuracy is the effect of divided voltage on stator resistors. At high speed, the primary reason is the effect of inaccuracy of k_e according to different motors. Therefore, a speed threshold is set. If *Spd_S* > *Spd_T_1*, the estimation algorithm shown in Fig. 5 is used and k_c is the output of the regulator to correct the estimated speed. If *Spd_S* < *Spd_T_2*, the estimation algorithm shown in Fig. 4 is used and v_c is the output of the regulator to compensate divided voltage on stator resistors. Avoiding repeatedly jumping, there is a hysteresis value between *Spd_T_1* and *Spd_T_2*. The selection of *Spd_T_1* and *Spd_T_2* is based on the period of speed loop, the number of poles of BLDC, and the number of Hall-effect sensors. Following rules can be used: 1) The longer the period

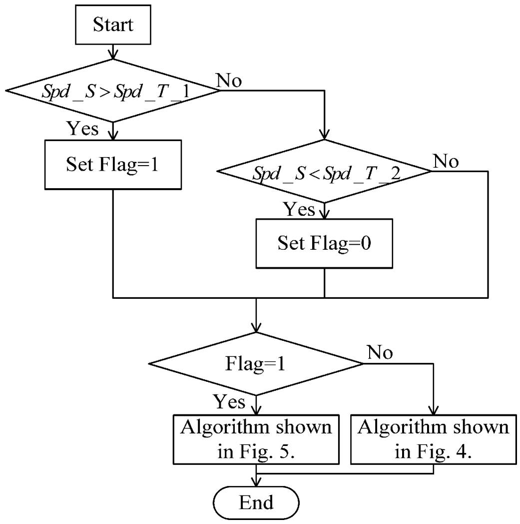


Fig. 6. Flow chart of estimation algorithm.

of speed loop, the smaller the value of *Spd_T_1*. 2) The more the number of the poles of BLDC motor, the smaller the value of *Spd_T_1*. 3) The more the number of Hall-effect sensors, the smaller the value of *Spd_T_1*. 4) The hysteresis value between *Spd_T_1* and *Spd_T_2* can be selected by experimental results. In the paper, the period of speed loop was 6 ms and it was selected by the engineering experience. For the BLDCs with four poles and three Hall-effect sensors used in the paper, the speed could be calculated once within a period of speed loop when the motor was running at 833 rpm. So the *Spd_T_1* was set to 800 rpm. In the experiment, there was 150 rpm speed ripple within a period of speed loop. Therefore, *Spd_T_2* was set to 600 rpm. Hysteresis band was set to 200 rpm which was a little larger than 150 rpm. Fig. 6 is the software flow chart.

TABLE I
MOTOR M2 RATINGS

Specifications	Units
Rated voltage	24V
Rated current	6A
Rated speed	3000rpm
Number of poles	4
Moment of inertia, *J*	0.0001963kg-m^2
Back EMF constant, *Ke*	0.048V-s/rad
Stator Inductance, *Ls*	0.2mH
Phase terminal resistance, *Rs*	0.25 Ω

TABLE II
MOTOR M1 RATINGS

Specifications	Units
Rated voltage	48V
Rated current	7.35A
Rated speed	4000rpm
Number of poles	4
Moment of inertia, *J*	0.000283kg-m^2
Back EMF constant, *ke*	0.08V-s/rad
Stator Inductance, *Ls*	0.38mH
Phase terminal resistance, *Rs*	0.27 Ω

IV. Simulated and Experimental Results

In order to verify the validity of the estimation algorithm, two different BLDC motors were used in simulations and experiments. The motor, whose parameters are shown in Table I, is named M1. The motor, whose parameters are shown in Table II, is named M2.

There are two-switch and three-switch PWM strategies for BLDC motors. The torque ripple of the three-switch PWM strategy is smaller than that of the two-switch PWM strategy. On the other hand, the maximum torque of the two-switch PWM strategy is larger than that of the three-switch PWM strategy and the two-switch PWM strategy is easier to be realized. Because the estimation algorithm proposed in the paper is implemented in the speed loop, the algorithm can be used in both PWM strategies. According to the demand of the China NSFC and NSTMP projects, the two-switch PWM strategy was selected in the simulation and experiment.

A. Simulated Results

The selection of proportional and integral parameters for the MRAC regulator is important. Simulations have been carried out with Saber to select proper parameters. The proportional parameter of the PI regulator in Fig. 5 is named k_{p1}, and the integral parameter is named k_{i1} and k_{p2} and k_{i2} are the parameters of the PI regulator in Fig. 4. In the simulations, k_e was tuned to 0.016 V·s/rad, k_c was tuned to 1, and v_c was tuned to 0 initially. It means that, according to (7), the estimated result at high speed is larger than the actual speed when $k_{p1} = 0$ and $k_{i1} = 0$. *Spd_T_2* is set to 600 rpm. *Spd_T_1* is set to 800 rpm. Simulated results of motor M1 at 2500 rpm with different k_{p1} and k_{i1} are shown in Fig. 7(a). Simulated results at 25 rpm with different k_{p2} and k_{i2} are shown in Fig. 7(b). According to Fig. 7(a), there was slight oscillatory response when k_{p1} and k_{i1} were too large. But the response time was too long if k_{p1} and k_{i1} were too small. According to Fig. 7(b), there was little influence when k_{p2} and k_{i2} were different. Therefore, in order

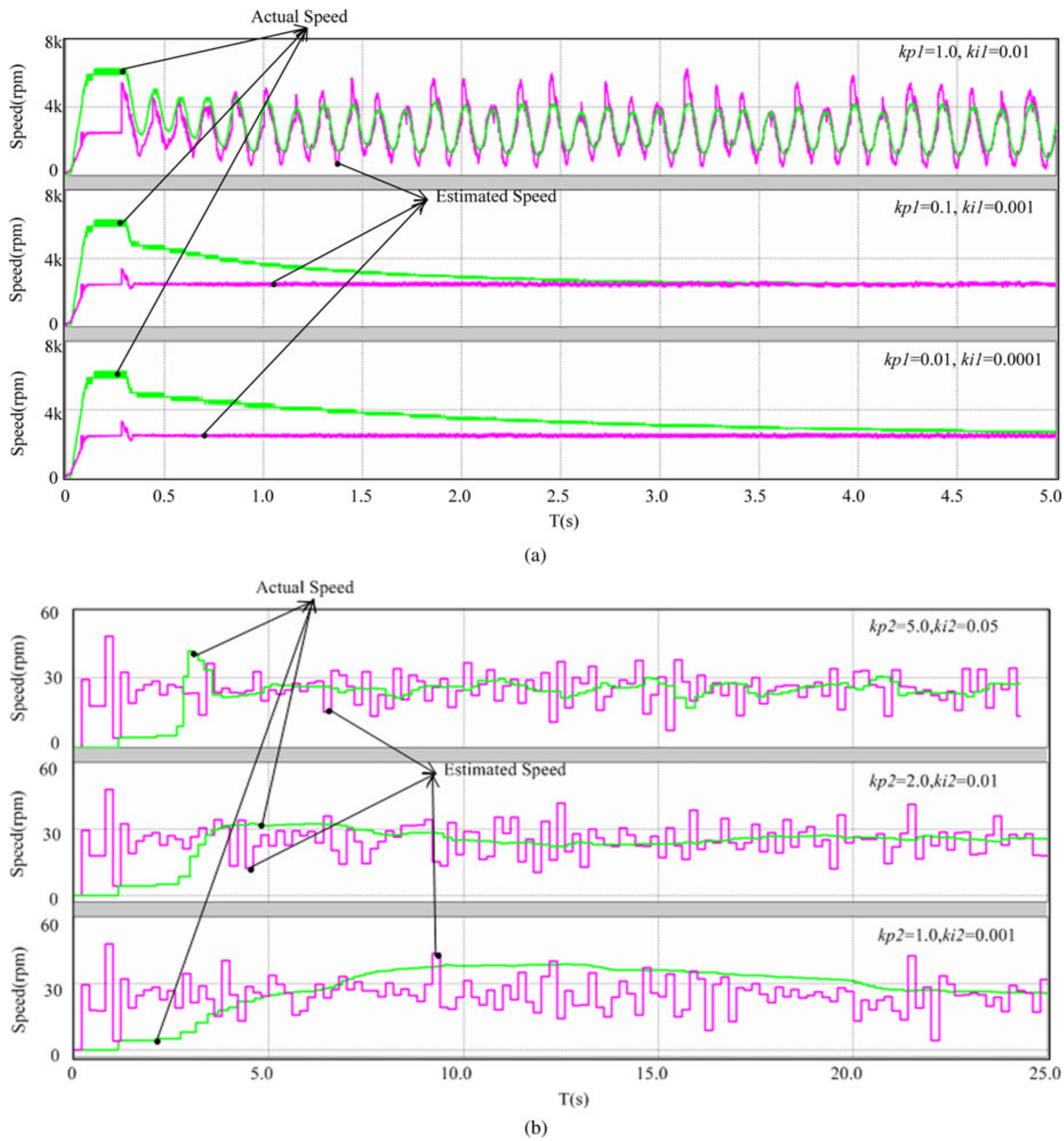


Fig. 7. Actual speed and estimated speed of the motor M1 at (a) 2500 rpm and (b) 25 rpm.

to avoid instability and shorten response time, the parameters for the MRAC regulators are selected to be

$$\begin{cases} k_{p1} = 0.1, \quad k_{i1} = 0.001 \\ k_{p2} = 2.0, \quad k_{i2} = 0.01. \end{cases} \tag{9}$$

Fig. 8 gives the simulated results that reference speed changes from 0 to 2500 rpm at 0 s and 2500 to 25 rpm at 7.5 s. A same simulation of the motor M2 with the selected proportional and integral parameters was carried out too. Fig. 9 gives the simulation results. As shown in Figs. 8 and 9, the estimated speed reached the reference. But it was smaller than the actual speed which was far larger than the reference. When the proposed algorithm presented in Fig. 6 was active at 2.0 s, k_c was regulated to correct the back EMF coefficient and then both the estimated speed and the actual speed reached the reference. When the actual speed was smaller than *Spd_T_2*, v_c was regulated to compensate the divided voltage of stator resistors and the motors M1 and M2 could run in stability at 25 rpm.

Fig. 10 gives the simulation results that the stator resistances of motors M1 and M2 were changed at 25 rpm. Referring to Fig. 10(a), the stator resistance was changed from 0.27 to 0.54Ω. The estimated speed always followed the actual speed. This was

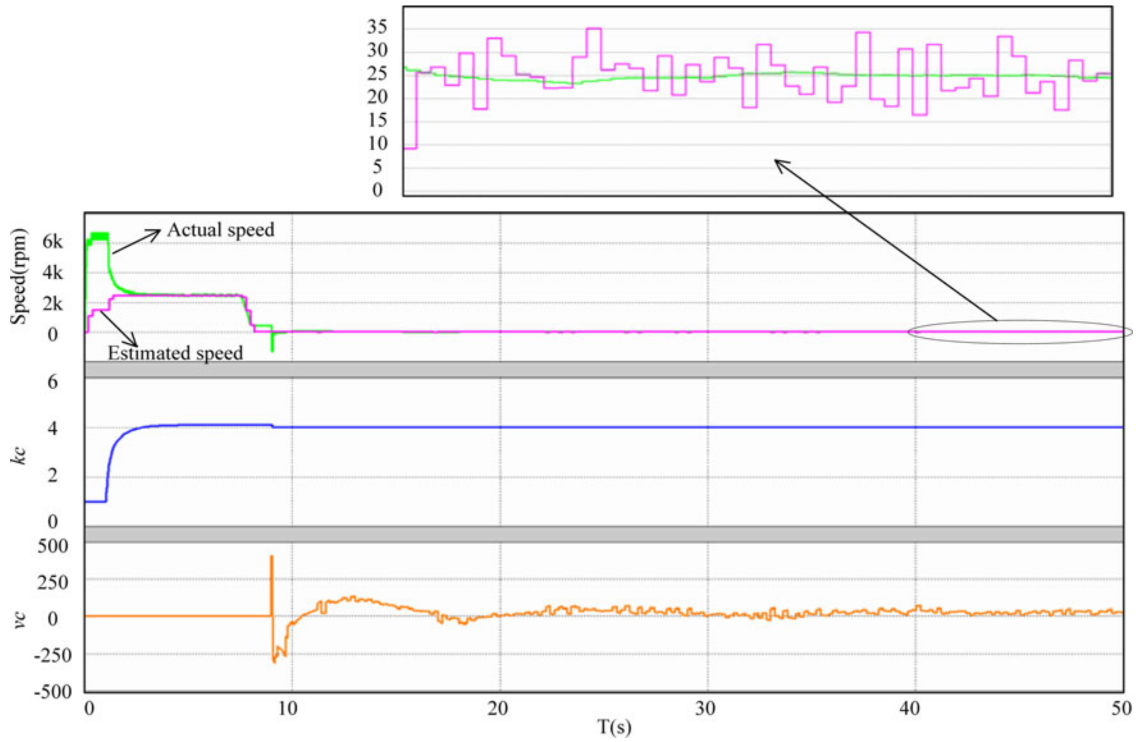


Fig. 8. Speed ranges from 2500 to 25 rpm with the motor M1.

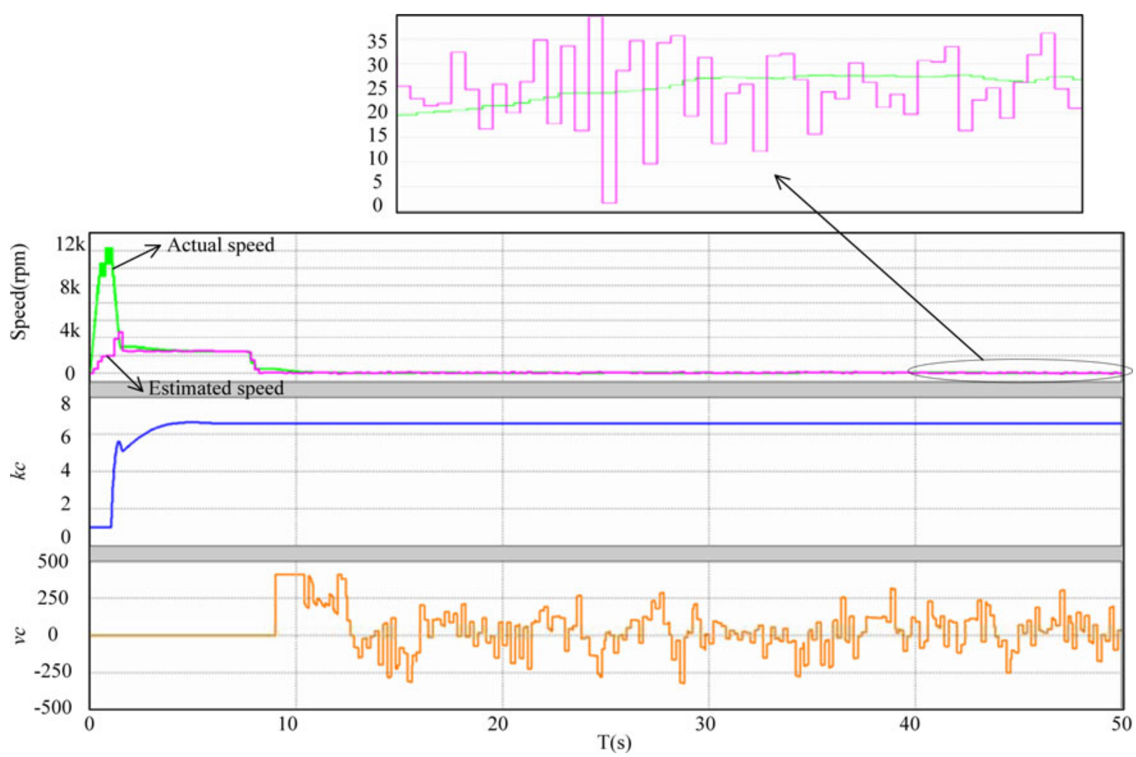
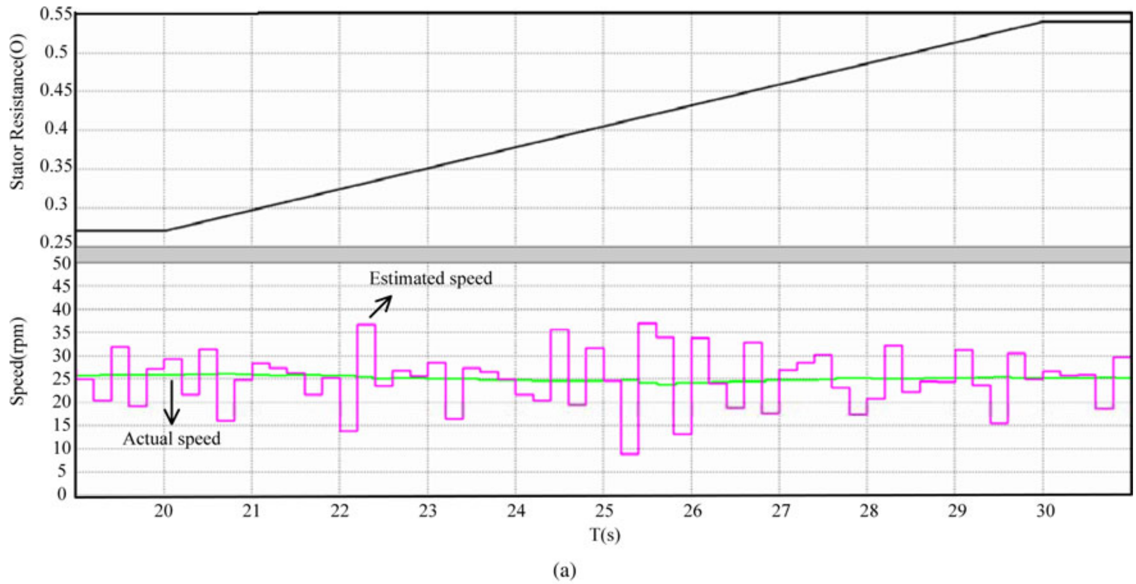


Fig. 9. Speed ranges from 2500 to 25 rpm with motor M2.

also found in Fig. 10(b) where the stator resistance was changed from 0.25 to 0.5Ω. The estimation algorithm is not affected by the stator resistance.

The above simulation results verify the fact that the proposed speed estimation algorithm based on MRAC can work validly not only at high speed but also at very low speed. The drive system based on the proposed estimation algorithm can make BLDC motors run in very wide speed range. Moreover, motors with different back EMF coefficients have little influence on the performance of the algorithm.



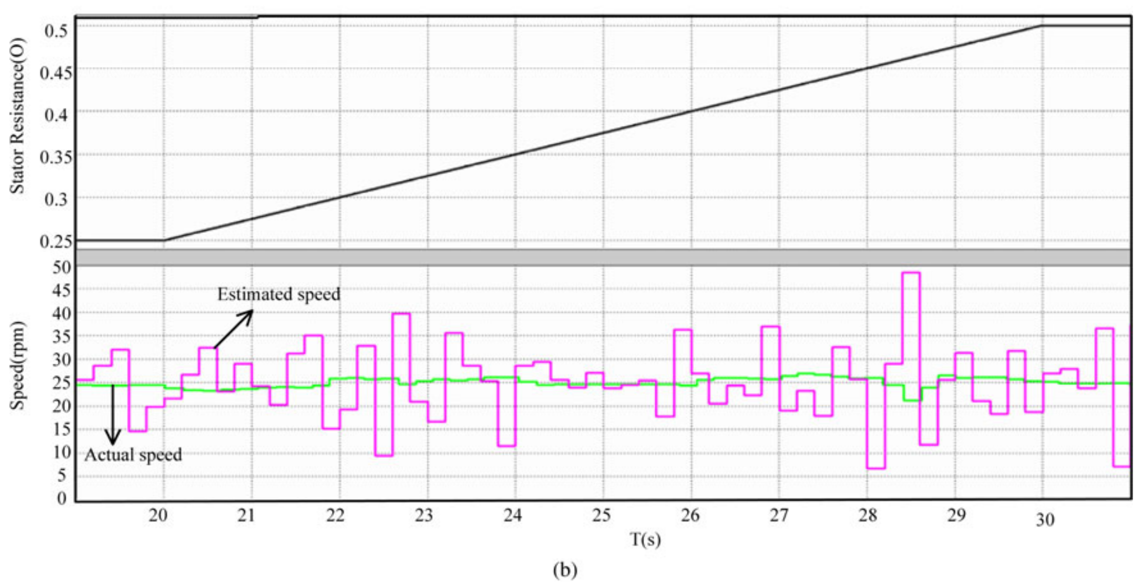


Fig. 10. Estimated speed with variation of the stator resistance (a) the motor M1 (b) the motor M2.

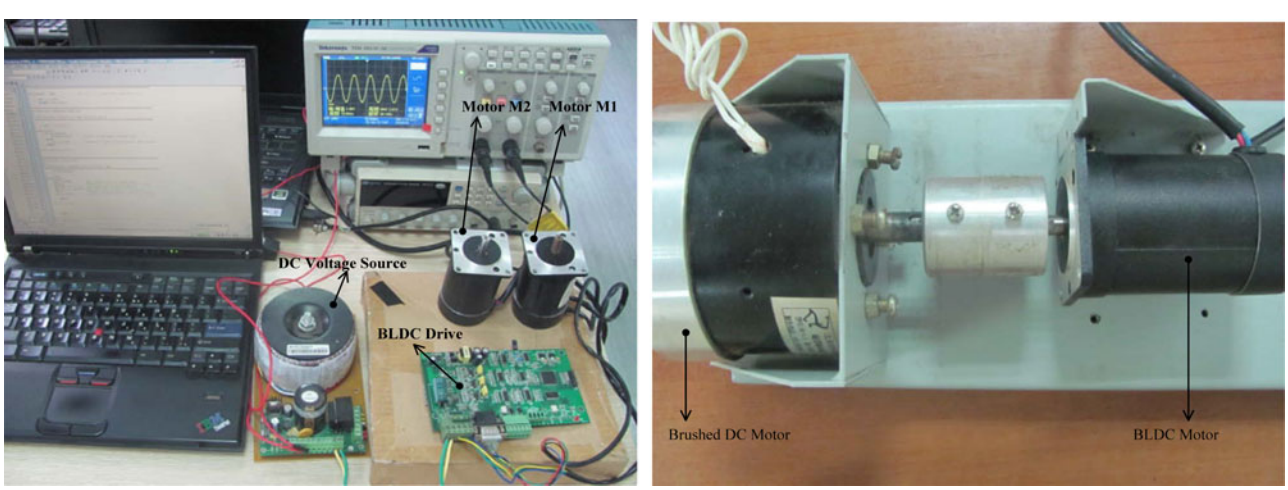


Fig. 11. Experiment Setup.

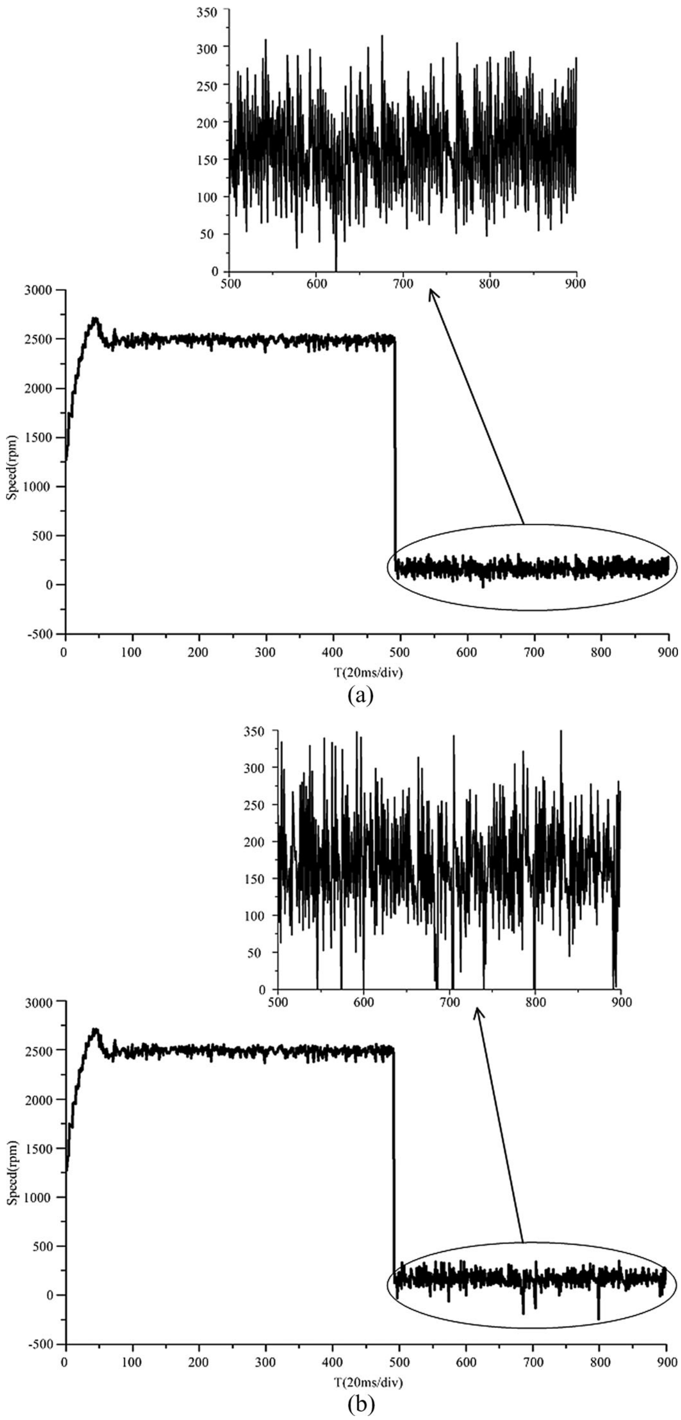


Fig. 12. Speed sketch without the proposed algorithm (a) the motor M1 (b) the motor M2.

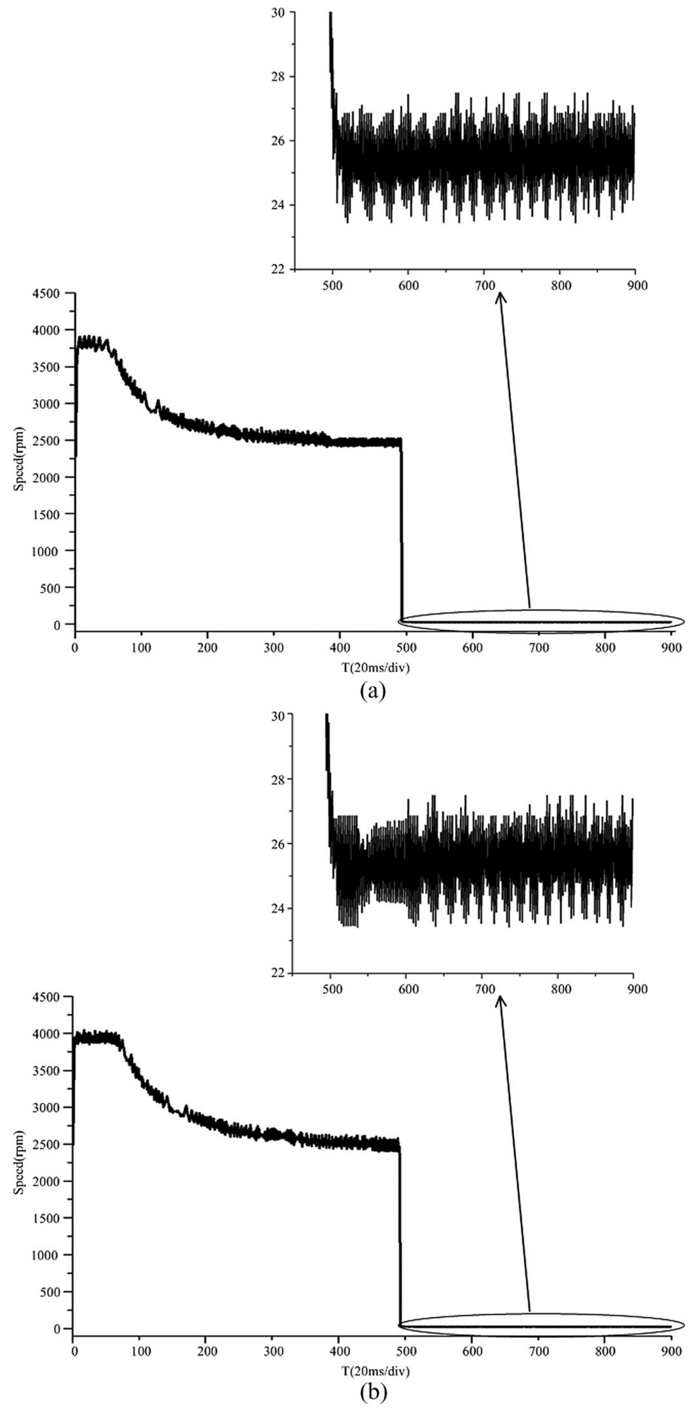


Fig. 13. Speed sketch with the proposed algorithm (a) the motor M1 (b) the motor M2.

B. Experimental Results

Fig. 11 gives the experiment test setup which was made up of a MOSFET inverter and a fixed point digital signal processor (DSP) controller TMS320F2806. The period of PWM is 50 μs and the period of speed estimation is 1 ms. The mechanical arrangement consists of two BLDC motors and motor M1 is coupled to a brushed dc motor. The brushed DC motor is equipped with high resolution encoder which is 1000 pulse/round. In experiments, the actual speed was obtained from the encoder of the brushed motor and saved in the DSP.

First, experiments without the proposed algorithm were performed. The speed obtained by Hall sensors was used as the speed feedback. Fig. 12 gives the experiment results at 25 and 2500 rpm with the motor M1 and the motor M2. As shown in Fig. 12, both two motors could work well at high speed, but not at low speed. There existed obvious oscillation.

Second, experiments with the proposed algorithm were performed. The experiment results at 25 and 2500 rpm with the motor M1 and the motor M2. As shown in Fig. 13, motors M1 and M2 can both work well at high speed as well as low speed. Comparing Figs. 12 with 13, the actual variation of the experiment with the proposed algorithm was smaller and more even at high speed and the actual speed was stable and reached the reference at low speed.

V. Conclusion

In this paper, a novel speed estimation algorithm based on MRAC is introduced. The proposed algorithm includes two regulators. One regulator corrects back EMF coefficient at high speed. The other regulator compensates the divided voltage of stator resistors at low speed. In this way, the estimation algorithm can work validly at both high speed and very low speed. The drive system with the proposed algorithm widens the speed range of BLDC motors. Moreover, it is not needed to tune parameters according to motors with different back EMF coefficient when using the estimation algorithm.

Extensive simulation and experiment have been performed and the results verify that the estimation algorithm proposed in this paper is effective.

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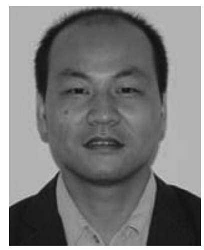

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