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Improved Speed Predictive Control for the Brushless DC Motor Adjusting Speed Study

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Abstract: Brushless DC motor not only had the superior speed performance of DC motor but also overcame the inherent shortcomings of mechanical reversing device. Therefore, it had many applications in many occasions especially small and medium-power drive systems. In this study, an adjusting speed method of speed prediction with PI control was given. Because the current control signals can be adjusted according to speed trends, the anti-disturbance capacity of control system improved significantly. The most important study was the improvement for speed forecasting methods and the previous time variation increased law of motor speed was used to predict motor speed in the future. At last, the motor speed control was realized. It was easier compared with the traditional predictive control theory. The result of reducing the amount of calculation, in the case of a small perturbation error, was obtained. By MATLAB contrast simulation, the superiority of both the speed forecasting methods and the way of control were demonstrated. Seen from the waves, the response of speed was quicker and the anti-disturbance capacity was enhanced.

Key words: Brushless DC motor, PI control with speed predictive, multistage incremental prediction method, anti-disturbance

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INTRODUCTION

Brushless DC motors not only had excellent speed adjusting performance but also overcame the mechanical reversing device shortcomings. Therefore brushless DC motor research has been widely paid attention to. Predictive control has begun to develop a new class of control algorithms since the 1980s. The algorithm was produced in the practical application of industrial process control and it was continuous improvement closely integrated with the industrial applications (Niu *et al*., 2012). The multi-step prediction, rolling optimization and feedback correction control strategies were used in the predictive control, so it has the advantages of controlling effect, robustness and less demanding on the model accuracy. PI control has the advantages of simple, easy to use, adaptable and robust. However, in the complexity control systems of nonlinear, time-varying, coupling and parameters with structural uncertainty, the effect of adjusting speed was always less than ideal (Yuanxi *et al*., 2012). In this study, the combination of the conventional PI control with the new predictive control was used in a brushless DC motor speed control system which made the anti-disturbance capacity of the system a good improvement (Ansarpanahi *et al*., 2008).

SPEED CONTROL SYSTEM ESTABLISHED

System model of brushless DC motor: The air-gap magnetic, back EMF and current of brushless DC motors are non-sinusoidal (Asseu *et al*., 2011). Directly use the motor itself phase variable to establish the mathematical model which is simple and has a high accuracy. Three-phase winding voltage balance equation can be expressed as Eq. 1:

$$\begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} = \begin{bmatrix} R_S & 0 & 0 \\ 0 & R_S & 0 \\ 0 & 0 & R_S \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L_A & L_{AB} & L_{AC} \\ L_{BA} & L_B & L_{BC} \\ L_{CA} & L_{CB} & L_C \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \quad (1)$$

The equation: u_A, u_B, u_C are the stator phase winding voltage, i_A, i_B, i_C are the stator phase winding current. e_A, e_B, e_C are stator phase winding electromotive force. R_S is the three-phase winding resistance. $L_A = L_B = L_C$ is the three-phase windings inductance, respectively.

$$u_{AB} = (e_A - e_B) + 2R_S i_A + 2L_S \frac{di_A}{dt} \; E = e_A - e_B = C_e \Phi_\delta n$$

$$n = \frac{U_d - 2\Delta U - 2I_A R_A}{C_e \Phi_\delta}$$

It can be seen from the brushless DC motor speed equation that the effect is better by the way of using

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Corresponding Author: Guangjie Fu, School of Electrical Engineering and Information, Northeast Petroleum University, Heilongjiang Daqing, 163318, China variable voltage to control the speed, in which smooth adjusting speed can be achieved, meanwhile the system is relatively stable (Liu and Liu, 2013):

$$T_e = \frac{P_e}{\Omega} = \frac{2E_p I_A}{\Omega} = K_T I_A \tag{2}$$

Electromagnetic torque equation of the brushless DC motor is the same with the ordinary brush DC motor that the electromagnetic torque is proportional to stator current. Therefore, brushless DC motor has the same excellent control performance with brush DC motor. The regulation characteristics of the brushless DC motor is a straight line.

Brushless DC motor speed control system under the predictive control: The motor speed can be changed smoothly by the way of adjusting voltage to control the speed. Meanwhile, because the electromagnetic torque of the brushless DC motor is directly proportional to the rotor current, the motor load torque signal feedback is helpful to improve the load capacity of the motor. In order to improve the speed control system quickly and anti-disturbance capacity, the design of the speed control system here takes the structure of double-loop.

The outer is speed ring, where the combination of speed prediction and PI control is used. The inner is torque feedback control, where the size of the load torque is depended on to control the winding current, in order to achieve greater stability. System block diagram is shown in Fig.1.

According to the given speed, the current time actual speed of the motor and the speed a moment ago, the size of the motor speed in the next time can be extrapolated by the prediction means, better guiding control motor speed. Ultimately, DC power supply voltage is controlled by the PI controller to change the motor speed. In addition, the torque contrast block is used, where the load torque is contrast to the electromagnetic torque obtained from motor current and the control signal is produced according to torque error. This block further improves the load capacity of the motor. Under the combined effect of double-loop, the stability and the load capacity of speed control system will be significantly enhanced.

IMPROVEMENTS TO SPEED CONTROL SYSTEM

Basic principle of predictive control: Predictive control is a predictive control algorithm that use variation trend to regulate. Predictive control has a variety of forms in practical application but no matter what form, all can be summarized as predictive models, rolling optimization, error correcting three basic characteristics. Here mainly for brushless DC motor speed to predict and then speed control can be achieved. The role of prediction models is predicting the output in the next period of time. Prediction model provides prior information for predictive control which can control the form of output, so as to achieve the purposes that the expected future time output follows the reference trajectory. Figure 2, for a given future control sequence 1, you can get the output trajectory 2 under a control strategy (Li, 2010).

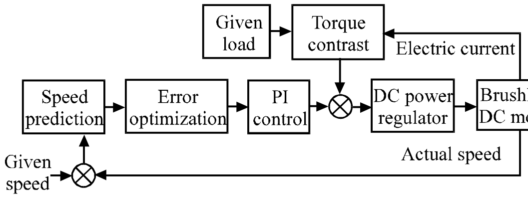

Fig. 1: Block diagram of brushless DC motor speed adjusting system

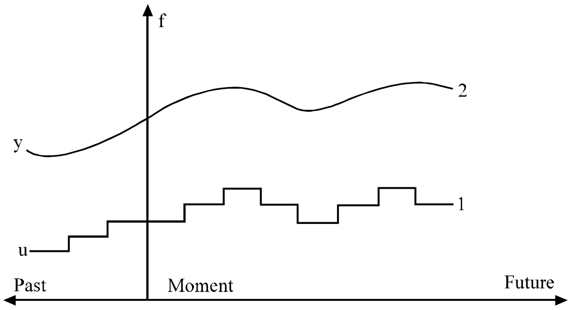

Fig. 2: Basic principle of the predictive control

In general prediction model, starting from step response speed, dynamic characteristics of the speed is represented by a series of dynamic factor a_1, a_2, ..., a_p, where "p" is the length of the model time domain. a_p is the coefficient that sufficiently close to steady state values, shown in Fig. 3.

If at the time k-i(k≥i) enter n(k-i), Then Δn(k-i) contribution to the output y(k) is Eq. 3-5:

$$y(k) = \begin{cases} a_i \Delta n(k-i) & (1 \le i < p) \\ a_p \Delta(k-i) & (i \ge p) \end{cases} \tag{3}$$

$$y(k) = \sum_{i=1}^{p-1} a_i \Delta n(k-i) + a_p \Delta n(k-p) \tag{4}$$

Use the equation above to get the n-step forecast of y(k+j), (n<p):

$$\hat{y}(k+j) = \sum_{i=1}^{p-1} a_i \Delta n(k+j-i) + a_p \Delta n(k+j-p) \quad (j=1,2,\ldots,n) \tag{5}$$

This estimate principle is very complex, the large amount of computation and sometimes the control input

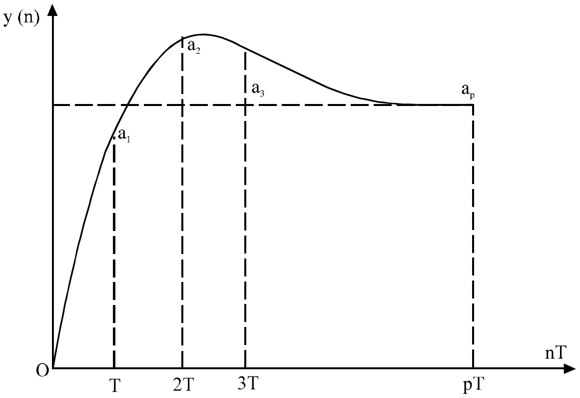

Fig. 3: Curve with dynamic coefficient

can not be achieved. In order to use less amount of computation to achieve the best control results, predictive control use the rotational speed of the motor here. In order to make predictions more accurate, here the multi-step increments in a predictable manner is used.

Improved predictive control method

Second-order delta prediction method of speed: Assuming the actual predictive control, we get the motor speed of current time is n_0, the motor speed at the previous moment T is n_{-1} and the motor speed at the previous moment 2T is n_{-2}. According to these conditions above the actual speed n_1 of the motor at a later time T will be predicted. The previous time T to the current time period, the amount of change in motor speed is Eq. 6:

$$\Delta n_{0-1} = n_0 - n_{-1} \tag{6}$$

In rough projections, we can predict a motor speed in the later time T approximation is Eq. 7:

$$n_1 = n_0 + \Delta n_{0-1} \tag{7}$$

One-step increment prediction simply uses the increment of motor speed to predict the motor speed the next time, such one-step prediction mode only in the case of speed changes linearly with time, the error was relatively small. In the case of a nonlinear time-varying speed, the error of this prediction way is relatively big. To make the prediction speed as possible as close to the actual motor speed in the next, we further use of high-level speed increment change. Second-order forecast diagram is shown in Fig. 4.

During the period from the previous time 2T to the previous time T, The amount of change in motor speed is:

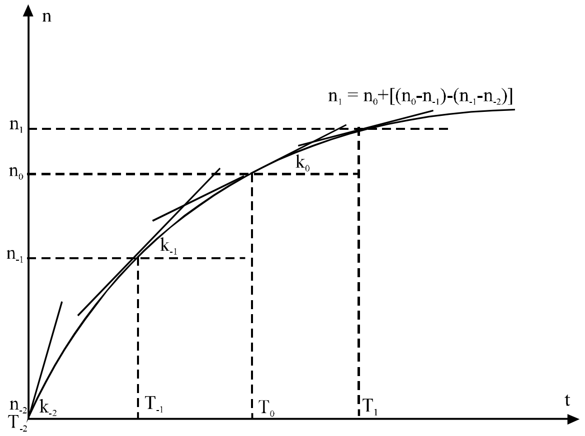

Fig. 4: Principle of predicting motor speed with second-step increments

$$\Delta n_{-1-2} = n_{-1} - n_{-2} \quad \Delta n^{1}_{0-2} = \Delta n_{0-1} - \Delta n_{-1-2}$$

And then the increments of speed increase from the current time to later time can be predicted Eq. 8:

$$\Delta n_{1-0} = \Delta n_{0-1} + \Delta n^{1}_{0-2} \tag{8}$$

Then, the motor speed at a later time is Eq. 9:

$$n_1 = n_0 + \Delta n_{1-0} \tag{9}$$

Here the second-step increments of speed are used to predict the speed in the future, compared with the first-step, the prediction future speed is closer to the actual motor speed. At the same time, the smaller the value of the selected time interval T, the closer predicted value of the speed is to the actual speed of the motor in the future but the greater amount of computation. When the time interval infinitely is close to zero, then the predicted speed error is close to zero. If the slope is incorporated k here, then:

$$k_{0-1} = \lim_{T\to 0, T\neq 0} \frac{n_0 - n_{-1}}{T} \approx \frac{d\Delta n_{0-1}}{dt} \quad k_{-1-2} = \lim_{T\to 0, T\neq 0} \frac{n_{-1} - n_0}{T} \approx \frac{d\Delta n_{-1-2}}{dt}$$
$$\Delta k = k_{0-1} - k_{-1-2} = k_{1-0} - k_{0-1} \quad k_{1-0} = k_{0-1} + \Delta k$$

So the speed of the motor predicted the next moment Eq. 10:

$$n_1 = k_{1-0} T + n_0 \tag{10}$$

In the case of second-step increment, estimating the motor speed in the next time T basically meet the error range. If more stringent requirements in the error, you can also increase the order.

So as to reach the third order, fourth order so that a higher number of bands, in which way, the error between the predictive value of speed and actual speed of the motor next time is smaller. But will increase the amount of computation at the same time. In practical applications, in the case of meeting the needs of the error premise, a smaller number order should try to use.

Speed prediction for n steps promoting: This prediction method will be extended to higher-step situation. Defined in the current time, a T time ago, 2T time age, 3T time ago…, the actual speed of the motor, respectively, n_0, n_{-1}, n_{-2}, n_{-3}......then:

$$\Delta k_{0-1}=\frac{n_0-n_{-1}}{T},\ \Delta k_{-1-2}=\frac{n_{-1}-n_{-2}}{T},\ \Delta k_{-2-3}=\frac{n_{-2}-n_{-3}}{T},\ \Delta k_{-3-4}=\frac{n_{-3}-n_{-4}}{T}$$

$$\Delta^2 k_{0-1-2}=\frac{\Delta k_{0-1}-\Delta k_{-1-2}}{T},\ \Delta^2 k_{-1-2-3}=\frac{\Delta k_{-1-2}-\Delta k_{-2-3}}{T},\ \Delta^2 k_{-2-3-4}=\frac{\Delta k_{-2-3}-\Delta k_{-3-4}}{T}$$

$$\Delta^n k_{0-1-2-\ldots n}=\frac{\Delta^{n-1}k_{0-1-\ldots-(n-1)}-\Delta^{n-1}k_{-1-2-\ldots-n}}{T},\ \Delta^n k_{-1-2-\ldots-(n+1)}=\frac{\Delta^{n-1}k_{-1-2-\ldots-n}-\Delta^{n-1}k_{-2-3-\ldots-(n+1)}}{T}$$

And then release:

$$\Delta^{n+1}k=\Delta^n k_{0-1-2-\ldots n}-\Delta^n k_{-1-2-\ldots-(n+1)},\ \Delta^n k_{1-0-2-\ldots-(n-1)}=\Delta^{n+1}k+\Delta^n k_{0-1-2-\ldots-n}$$
$$\Delta k=k_{1-0}-k_{0-1},\ k_{1-0}=k_{0-1}+\Delta k$$

Finally get:

$$n_1=k_{1-0}T+n_0 \tag{11}$$

With the incremental increase in the order, the data needed is more. When the order tends to infinity, the predicted motor speed approaches the actual speed value of the later moment.

By the method above, you can get the motor prediction speed at a later T time. Similarly, if we assume that after a time 2T, the prediction speed of the motor is n_2. The calculation algorithm of prediction speed n_2 and n_1 are similar. When calculating the value of n_2, n_1 can be used as a known quantity. Although the predictive value n_1 is also obtained by calculating and see a latter time T as the current time, the derived formula above can be used to calculate n_2. If you predict the future motor speed for longer, then calculate n_3, n_4 ......until it reaches the length of time of the prediction:

$$n_2=k_{2-1}T+n_1,\ n_3=k_{3-2}T+n_2$$

Connection these points, a trend of the motor speed for future time can be approximated. But as time continues to increase in the future, the further prediction speed of the motor is bound to rely more on the speed value that has been predicted. That is to say, the next moment predicted farther from the current and then the error of the prediction value of the motor speed will increase as the duration. Credits of the prediction speed will decrease.

Combination of forecast and PI control: The later time T, 2T, 3T ...... value of motor speed predicted can be gotten by the way of multi-step increments. With the passage of time, after a period T, latter T moment will become the current time, later 2T moment will become the later T moment...... After T time, the next time will be close to the current time T. And so on, the rolling optimization process of predictive control is achieved. In the constantly rolling optimization process, the actual speed of the motor is updated in real time. Then the value of the motor speed predicted is also constantly corrected. After getting the later time T, 2T...... value of the motor speed predicted, the next step is to apply the prediction speed to the control system.

Most of today's automatic control technology is based on feedback. In the past few decades, PID control is widely used in industrial control. In control theory and technology development today, more than 95% have a PID control loop structure in the industrial control and many of the advanced controls are based PID control. The traditional PID control uses the data of the current time to control the current time control system. If the predicted data obtained is taken to guide the current speed control time, the response will be quicker. Because the farther from the current moment in time, the lower the accuracy of the predicted speed. Therefore, when considering future time to the current control effect, more attention should be relatively taken to the predictive value near the current time. Thus, a predictive control and PI control serial control mode has been designed, the speed value predicted from the predictive control as part of the current control. Here:

$$\Delta N_0=n^*-n_0,\ \Delta N_1=n^*-n_1,\ \Delta N_2=n^*-n_2,\ \Delta N_n=n^*-n_n$$

The input of the PI control link is similar to Eq. 12:

$$N=\Delta N_0+\frac{\Delta N_1}{1^1}+\frac{\Delta N_2}{2^2}+\ldots+\frac{\Delta N_n}{n^n} \tag{12}$$

With the extension of the prediction time, the error of rotational speed obtained by prediction is greater. At last the credibility gradually decreased. When the time t→∞, the confidence will be close to zero.

SIMULATION ANALYSIS

Establish of the prediction model: Based on the speed control system schematics designed of brushless DC motor, MATLAB simulation model is established. Build a model predictive controller which takes second-order prediction method. The speed before 0.001 seconds was applied to predict the rotational speed of latter 0.001 sec. Figure 5 is the module of the speed prediction (Zhu and Zhang, 2011).

The rated speed of the brushless DC motor is 4000 rpm, rated voltage is 600 V, rated load is 10 N-m and the simulation time is 0.2 second. The brushless DC motor starts under no-load condition and join rated load 0.1 sec and generate disturbances. In considering the basis of adjustment time, overshoot, error and immunity, after repeated tests and 2% in the range of allowable error, the range of brushless DC motor speed is determined 1000-4000 rpm.

Analysis of simulation: In the case of the conventional PI control, the waveform is shown in Fig. 6 when the given motor speed is 3000 rpm.

The case of quick and stability of the system can be seen from the figure. The motor starting to steady nearby the given speed takes about 0.06 seconds. At 0.1 sec, the rated load is added. A relatively large disturbance occurs at the speed waveform about 500 rpm. Figure 7 is the waveform of the motor speed under the PI control with improved prediction speed.

Compared with the case of the conventional PI control in Fig. 6, the peak over shoot is similar but the quick and stability of the motor control system has been significantly improved in Fig. 7. The time is significantly shortened from starting the motor speed to achieve the given speed, less than 0.02 sec to reach steady state. At the same time, after adding the load torque, the motor speed perturbation is also significantly smaller than that under the conventional PI control, only about 200 rpm. So the motor speed waveform in Fig. 7 is better in the aspect of quick and stable. Figure 8 shows the speed waveform under the rolling optimization of real-time prediction.

From real-time predictive waveform view, the actual motor speed waveform is substantially coinciding with the waveform above. Just at the end of the ascent speed after starting, the forecasts accuracy has slight fluctuations. Figure 9 and 10 gives the real-time control waveform under the speed prediction at the different given speeds.

As can be seen from the above diagram, with the decline of the given speed, overshoot becomes larger and carrying load capacity gradually decreased. When the given speed reduced to 1000 rpm, speed error is close to

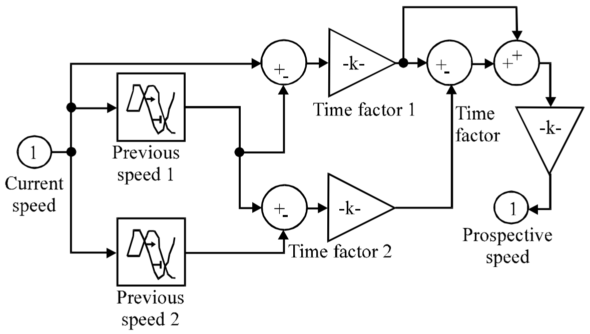

Fig. 5: Speed prediction module

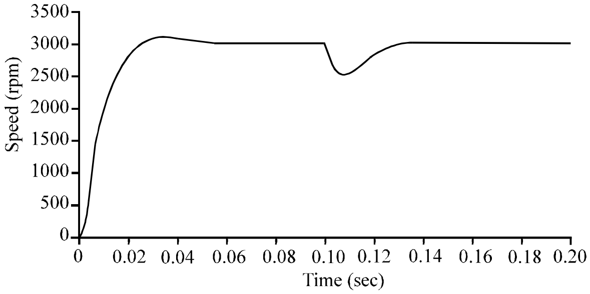

Fig. 6: Speed waveform under the PI control

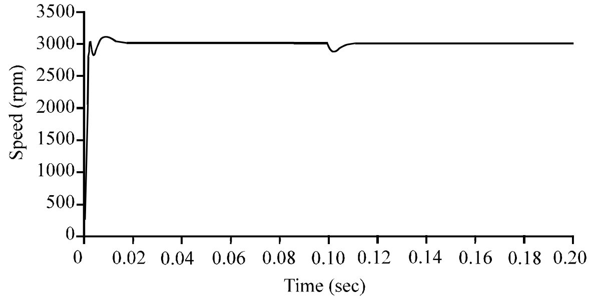

Fig. 7: Speed waveform under the improved prediction with PI control

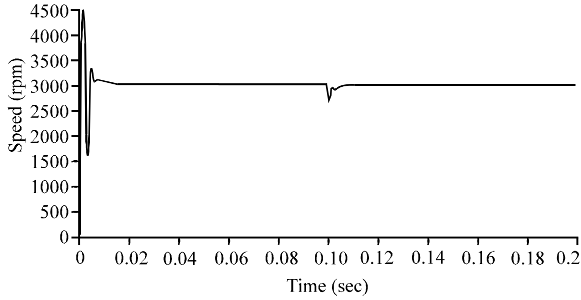

Fig. 8: Real-time prediction motor speed waveform

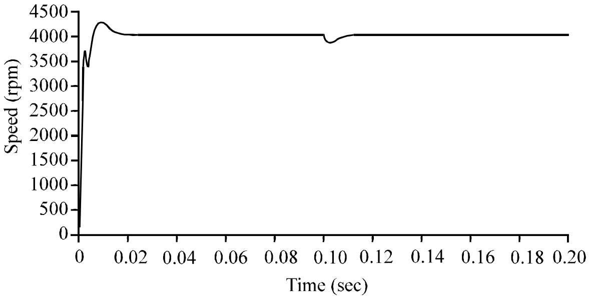

Fig. 9: Speed waveform given 4000 rpm

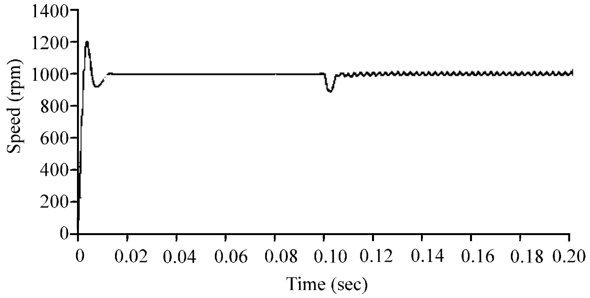

Fig. 10: Speed waveform given 1000 rpm

2% of the maximum allowable value. But compared to the conventional PI control, adjusting speed effect has been significantly improved.

CONCLUSION

This study based on the analyzes of the characteristics of the brushless DC motor speed control, the adjusting speed method of speed prediction with PI control was given. The speed forecasting methods have been mainly studied. Take use of the multi-stage incremental approach that can reduce the amount of calculation for speed prediction to guide the current PI control. Because PI parameters can be adjusted according to the speed trend rapidly, the motor speed has good anti-disturbance capacity and quicker response. In addition, the torque feedback is also used to reduce speed disturbance. These have been proved by mode simulation. The speed prediction with PI control method not only laid the foundation to better control of the brushless DC motor but also can guide the theory of prediction control.

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REFERENCES

Ansarpanahi, S., S.B.M. Noor and M.H. Marhaban, 2008. Stability study of model predictive control in presence of undesirable factors. J. Applied Sci., 8: 3683-3689.

Asseu, O., T.R. Ori, K.E. Ali, Z. Yeo, S. Ouattara and X. Lin-Shi, 2011. Nonlinear feedback linearization and observation algorithm for control of a permanent magnet synchronous machine. Asian J. Applied Sci., 4: 202-210.

Li, G.Y., 2010. Intelligent Predictive Control and its MATLAB Implementation. Publishing House of Electronics Industry, Beijing, China.

Liu, Z. and B.F. Liu, 2013. Robust control strategy for the speed control of brushless DC motor. J. Harbin Inst. Technol., 20: 90-94.

Niu, L., M. Yang, K.S. Liu and D.G. Xu, 2012. A predictive current control scheme for permanent magnet synchronous motors. Proc. CSEE, 32: 131-137.

Yuanxi, W., Y. Yali, Z. Guosheng and S. Xiaoliang, 2012. Fuzzy auto-adjust PID controller design of brushless DC motor. Phys. Procedia, 33: 1533-1539.

Zhu, C. and H. Zhang, 2011. Mathematical model and system simulation of the brushless DC motor. Proceedings of the 10th International Symposium on Distributed Computing and Applications to Business, Engineering and Science, October 14-17, 2011, Wuxi, China, pp: 409-411.