OPTIMIZATION OF CONTROL ALGORITHM FOR BLDCM IN THE SHIP

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Abstract. A speed-regulating system of BLDCM has been designed on the basis of the expert system. It involves nonlinear optimization and PID controller design. The design method is improved through the linear fitting of piecewise function and expert PID controller. The function of PID controller is enhanced according to the error of motor rotating speed. A real experiment has been conducted, and the output demonstrates that this controller is robust and reliable.

Keywords: BLDCM; PID controller; expert system; nonlinear optimization.

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Problem statement. The need to isolate the effect of ship motion interference in the stability of the satellite signal is usually used in the automatic servo system to overcome the effect of carrier on the satellite antenna in the process of movement. The antenna can accurately point to the satellite communication needs and keep the satellite communication link unblocked. The servo system has been controlled by stepper motor in the past, but it has many disadvantages: speed limit (speed will lead to lost step), running noise, complex process structure and so on. BLDCM has been widely used in many areas because of its advantages, such as fast dynamic response speed, simple structure and high efficiency. The servo system based on BLDCM control is going to become a new trend.

Latest research and publications analysis. Theoretically, the rotating speed of an ideal BLDCM is supposed to have a linear relationship with three-phase stator voltages. But actually its strong coupled parameters and high nonlinearity make it difficult to control its speed well. How to design a speed controller for BLDCM with a high performance and a low cost has been a hot point. Traditional PID controllers have been designed for BLDCM with a precise speed and robust stability. However, the traditional PID controller also has some disadvantages. It is not easy to select optimal PID parameters for a BLDCM controller.

THE ARTICLE AIM is to consider introduction of the self-adaptive expert PID control into a speed-regulating system of BLDCM. PID parameters will be changed according to the experiment.

Basic material. ***Nonlinear optimization of the real model of BLDCM.*** Based on the selected motor type, 57ZWX01, the stator windings are connected in the form of star, without a center line. The respective relation of the three-phase current can be written as follows:

$$i_a + i_b + i_c = 0 \text{ and } M_{i_a} + M_{i_b} + M_{i_c} = 0 \qquad (1)$$

According to the general principles of motor operation, the equations of the three-phase winding voltage with the state variables of the three-phase electric current in an ideal BLDCM can be described as follows:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} Ra & 0 & 0 \\ 0 & Rb & 0 \\ 0 & 0 & Rc \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + $$

$$+ \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad (2)$$

where u_a, u_b and u_c are the three-phase stator voltages, i_a, i_b and i_c are the three-phase stator phase electric currents, L is the three-phase stator inductance, M is the mutual inductance of each stator, R is the winding resistance of each phase stator, p is the number of pole pairs, and e_a, e_b and e_c are the three-phase stator electromotive forces.

The electromagnetic torque of the permanent magnet BLDCM is generated by the interaction of the current in the stator winding and the magnetic field produced by the rotor magnet. One phase square wave current and trapezoidal wave back electromotive force waveform is shown in Fig. 1. Current commutation is done by a six-step inverter as shown in a simplified form in Fig. 2.

Generally, the influence of inductance is ignored, and based on the following two equations

$$e_a = K_e \cdot n \text{ and } T_{em} = K_t \cdot i_a, \qquad (3)$$

and the symmetry of the three-phase stator voltages, equation (2) can be simplified as follows:

$$u_a = i_a \cdot R + e_a,\ u_a = R \cdot T_{em} / K_T + K_e \cdot n, \qquad (4)$$

where K_e is the counter-electromotive force constant, K_T is the electromagnetic torque constant, T_{em} is the BLDCM output torque, and n is the rotating speed of BLDCM.

In this work, to identify the expert system for BLDCM and implement control arithmetic, the experiment platform shown in Fig. 3 is constructed mainly based on two chips from ST and IR Inc., one is STM32F103C8T6 MCU and the other is IR2130S pre-driver. The controllable input to BLDCM system is pulse width value of PWM logic signals generated directly by the PWM module of MCU. The rotating speed of BLDCM is the measurement output, which can be calculated in time according to the optical-electricity encoder signal changes. Load torque variation is regarded as disturbance input to the BLDCM system. Considering one kind of BLDCM's application, the motor works under a constant load with an extra small load varying randomly in this experiment.

Under this circumstance, according to Kirchhoff Voltage Law, this voltage balance equation can be acquired easily as follows:

$$U_d = u_a + 2\Delta U_T,\ U_d = i_a \cdot R + e_a + 2\Delta U_T. \qquad (5)$$

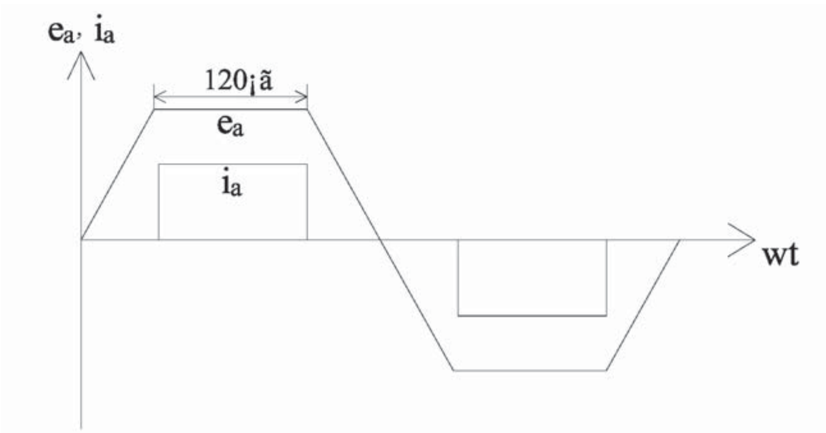


Fig. 1. One phase square wave current and trapezoidal wave back electromotive force waveform

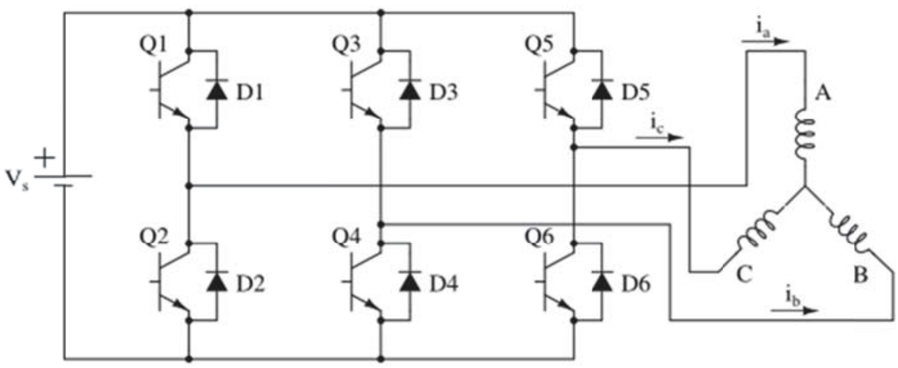


Fig. 2. Simplified BLDC drive scheme

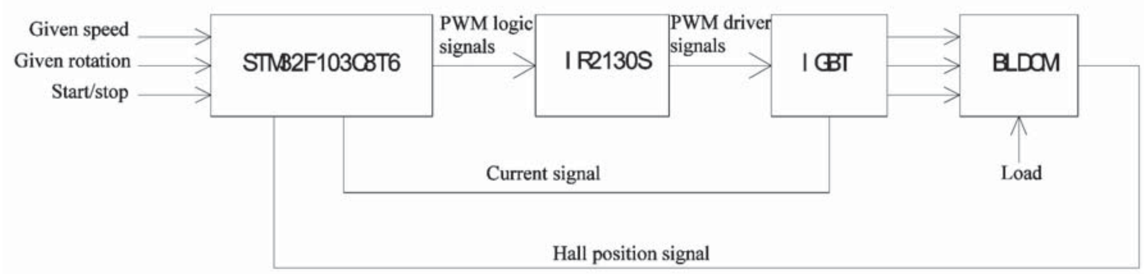


Fig. 3. Experiment platform

Combined with equation (3), the final equation has the following form:

$$U_d = R \cdot T_{em}/K_T + K_e \cdot n + 2\Delta U_T, \tag{6}$$

where U_d is the motor drive power voltage, ΔU_T is the voltage drop when IGBT is turned on, and it can be seen as a constant.

However, through the course of a real experiment, the speed-regulating characteristic of BLDCM is shown with the blue line of Fig. 3, which demonstrates a strong nonlinearity and uncertainty of BLDCM. However, according to the theory of linear fitting and the establishment of piecewise function, the partial linear relationship between U_d and the rotating speed n can be established as shown with the red line of Fig. 4.

Finally, the optimal piecewise linear approximation relationship between U_d and the rotating speed n can be expressed as follows:

$$n = \begin{cases} \dfrac{U_d}{U_{\max}} \cdot 9659 - \\ -1303 U_{\min} \le U_d < 0.425 \cdot U_{\max} \\ \dfrac{U_d}{U_{\max}} \cdot 2111 + \\ +2210, 0.425 \cdot U_{\max} \le U_d < U_{\max} \end{cases}, \tag{7}$$

where U_{max} is the upper limit of U_d, U_{min} is the lower limit of U_d. In this work, Umax equals 36 V, while U_{min} equals 4.89 V. All the output of the experiment is under the condition that the motor works under a very small load.

Design of the expert PID controller for BLDCM. A real BLDCM has strong nonlinearity and parametric uncertainty. Therefore, the conventional method of the PID controller design does not work well. By making good use of experience of the expert system, an optimized robust PID controller can be easily designed.

Taking advantage of the linear optimization, PID parameters can be easily implemented in the partial speed range. Furthermore, combined with the expert rules, the real output of BLDCM is steady and robust.

1. Motor start-up stage

At this stage, non-ideal trapezoidal waves of three-phase Hall signals get involved. The non-ideal three-phase Hall signals probably result in motor brake with a big noise. In this paper, it is solved by a fuzzy start. Generally, it is the incompletion of Hall signals that brings out the ineffective mode. Consequently, CPU cannot give the right switch signal that the motor will be braking. This situation happens only at the stage of BLDCM start-up because of the slow rotating speed at start.

A fuzzy start means that BLDCM starts without Hall signals, and CPU will implement delay procedures between two adjacent switching signal. At this stage, the system of BLDCM is under open loop control, which demonstrates that all the PID parameters are set to 0.

2. Motor accelerating stage

When the BLDCM starts up successfully, CPU will change switching signals according to Hall signals automatically. Then BLDCM will be in the acceleration phase. In this stage, the BLDCM's speed changes hugely. According to the expert system, the integral separation will be applied in adjusting the parameters of the PID controller. It means that the value of K_p is set as high as possible under the provision of zero overshoot, to make sure the accelerating speed is fast enough. Moreover, K_i is set to zero as well to avoid integral saturation which would result in shock of output speed.

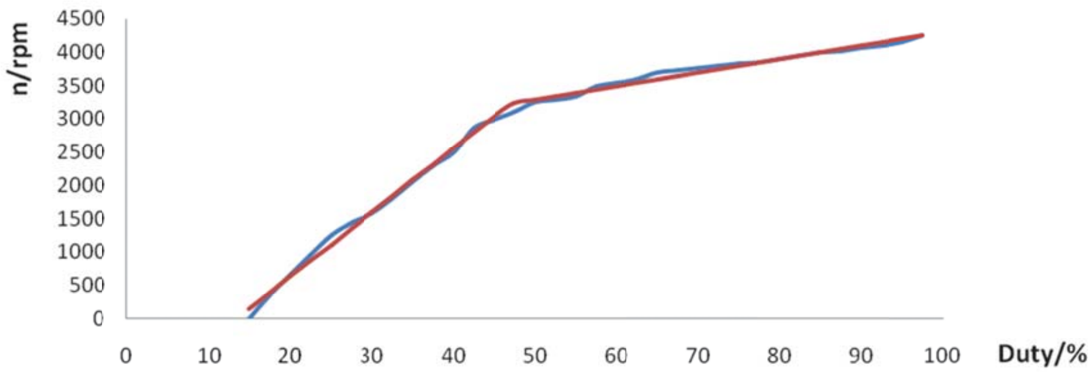


Fig. 4. Linear fitting and piecewise function establishment

3. Motor stable operation stage

At this stage, the rotating speed of BLDCM tends to stabilize. For this purpose, the integral parameter K_i must be introduced to eliminate static error of speed. However, if K_i is too large, it would bring about overshoot of output; if it is too small, the static error would not be eliminated effectively.

In all stages, Kd is set to zero. But if not, it may cause the damage of motor.

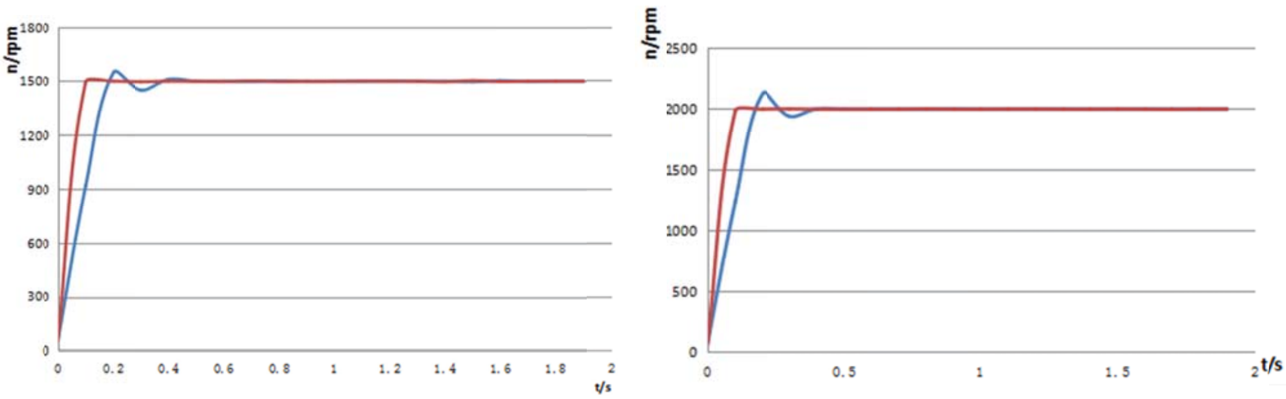
Experiment results. The real experiment platform is built up accordingly. The selected motor model is 57ZWS01, whose rated power is 50 W, rated speed is 3300 rpm, rated torque is 0.18 N*m. The optical encoder for speed measurement is from Tamagawa FA-Coder Company; its model is OIH48-2500P6-L6-5V.

The conventional PID algorithm and the expert PID algorithm are all implemented in the platform. The given speed is set to 1500 rpm and 2000 rpm. The results are shown in the following figures.

Red line is the expert result, and the blue one is the conventional PID experiment result.

From Fig. 5, it can be revealed that the overshoot is nearly zero, adjustment time is about 100 ms and there is no steady error in the expert PID implementation. In comparison with the expert PID result, it can be seen that the conventional PID controller has a problem of overshoot and adjustment time. Partial drawing of 2800 rpm to 3000 rpm is shown in Fig. 6; it is obvious that the speed is steady.

The expert PID controller implemented with STM32F103C8 MCU performs stably and reliably. When comparing, the expert PID controller works better than the conventional PID controller.



a) *b)*

Fig. 5. Real output of conventional PID and expert PID:
a — under 1500 rpm; *b* — under 2000 rpm

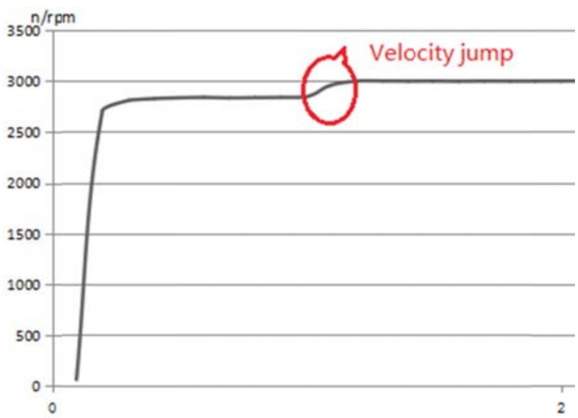


Fig. 6. Partial drawing of 2800 rpm to 3000 rpm

CONCLUSION. Overall, the process of the expert system identification in this paper operates well and the acquired expert PID model makes each of PID parameters play an important role as far as possible. Thus, the output of the experiment is quite precise. It can be used as a reference for model identification of other motor control systems. On the other hand, the approach to optimize linear relationship between input and output can also be profitable when designing controllers for other nonlinear systems. Finally, the speed controller design method for BLDCM is inexpensive and feasible. However, due to limitations of the test conditions, it can not be verified on board, and will be further verified and optimized in the future works.

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