Brushless DC Motor Control Strategy for Electric Vehicles

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Abstract

A self-adaptive fuzzy proportional integral derivative (PID) control method based on genetic optimization is proposed to solve the problem of low precision and low anti-jamming capabilities of the brushless direct current (DC) motor control system of electric vehicles. A double closed-loop speed control system model of the drive motor is established based on an analysis of the mathematic model of a permanent magnet brushless DC motor. Adaptive fuzzy PID control is introduced. The fuzzy membership function is optimized by the genetic algorithm and referred to as the optimized adaptive fuzzy PID control method. The design and simulation of the system are realized by using MATLAB/Simulink. Results show that in the same environment, the genetic algorithm with adaptive fuzzy PID control has better dynamic and static performance than ordinary and fuzzy PID. It has a good speed and anti-interference ability in a typical city driving environment.

Keywords: electric vehicle; permanent magnet brushless DC motor; adaptive fuzzy PID control; genetic optimization

1. Introduction

At present, new energy vehicles, especially hybrid vehicles and pure electric vehicles, are developing rapidly. Research on precise control of vehicle drive motors has also increased. The nonlinear characteristics of existing vehicle drive motors and the use of brushless direct current (DC) motor are investigated by considering the motor torque, power density, cost, and other factors, as well as the brushless DC motor with strong coupling [6]. The traditional control of brushless DC motor uses a simple structure of proportional integral derivative (PID) control. Thus, the general industry satisfies some of the robustness requirements. However, the control accuracy of this motor, as the vehicle’s power source, cannot satisfy the control and comfort requirements of drivers [5].

Current domestic and foreign research on brushless DC motor control mainly focuses on the application of fuzzy control algorithm to control the motor. However, although fuzzy control does not require a precise mathematical model and can overcome the influence of nonlinear factors, it also has strong robustness to changes in the parameters of the regulated object [8]. However, the summary of fuzzy rules and the adjustment of fuzzy membership functions mainly rely on experience. Considerable subjectivity exists, and simple fuzzy control has some steady-state error and low steady-state accuracy [2].

An adaptive fuzzy PID control method is proposed to address the deficiency of ordinary PID control and fuzzy PID on motor control. The genetic algorithm (GA) is used to optimize the fuzzy membership function. The control method is applied to the brushless DC motor of the electric vehicle, and the double closed-loop control system of speed and current is established. The motor control precision is optimized to satisfy the requirements of fast motor control response and small overshoot.

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2. Motor mathematical model

A permanent magnet brushless DC motor with trapezoidal back EMF and rectangular current waveform is simplified by using the nonlinear rotor and stator mutual inductive effect. The cogging effect is simplified after excluding the uniform winding within the stator. The armature reaction is ignored, and the hysteresis and eddy current losses are not considered in the three-phase winding symmetry. The simplified equation for the motor winding voltage balance is given as follows:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & r \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

(1)

The winding voltage of the stator is expressed by $u_a, u_b, u_c$, the stator winding current is expressed by $i_a, i_b, i_c$, and the stator winding EMF is expressed by $e_a, e_b, e_c$. The inductance of each phase winding, the mutual inductance between any two phase windings, and the differential operator are expressed by $L, M, p$, respectively. The brushless DC motor between the three-phase windings without median is obtained as follows:

$$i_a + i_b + i_c = 0$$

(2)

$$Mi_a + Mi_b + Mi_c = 0$$

(3)

Therefore, the new motor winding voltage balance equation is as follows:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & r \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

(4)

Furthermore, the torque equation and the equation of motion of the simplified brushless DC motor are expressed as follows:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{w}$$

(5)

$$T_e - T_L = J \frac{d\omega}{dt} + B\omega$$

(6)

where $U_a$ is the armature voltage, $L_a$ is the armature inductance, and $i_a$ is the armature current. The electromagnetic torque of the motor is expressed by $T_e$. The angular velocity of the rotor is expressed by $\omega$. The load torque is expressed by $T_L$. The motor’s own moment of inertia is expressed by $J$.

3. Double Closed-Loop Control System Based on Adaptive Fuzzy PID

3.1. System structure

The maximum current of an electric vehicle brushless DC motor is limited by the inverter power switch tube. Thus, the current maintains the maximum allowed value at start-up, resulting in maximum acceleration. The current should be reduced when the speed reaches a steady state. The motor drive torque and load balance reduce the system oscillation, and the motor achieves the steady-state operation. Therefore, a series of speed and current regulators should be introduced into the motor system to form a double closed-loop control system. A dual closed-loop control system is shown in Figure 1. The inner ring represents the current loop, and the outer ring represents the speed ring. The system design principle is that the inner ring and then the outer ring [7].
Current loop using current hysteresis tracking PWM control. The motor and the positive terminal of the DC bus are connected, and the current starts to increase when the difference between the reference current and the actual current reaches the positive edge of the hysteresis width. However, the motor and the DC bus negative terminal connected to the current begin to decline when the difference between the instantaneous current value and the actual current reaches the hysteresis width (minus the edge). The appropriate hysteresis width is selected to allow the actual current to continue to track a given current waveform, which is the current closed-loop control \[3\]. The current loop should obtain an excellent follow-up performance according to the requirements of the control system, and the influence of electromotive force should be ignored. The current loop is calibrated to be a typical first-order system in the design. The PID controller is adopted as the current regulator. The control is easy. When the frequency is high, the response is fast. Its open-loop transfer function is as follows:

\[
W_{op}(s) = \frac{K_i (\tau_i s + 1)}{\tau_i s} + \frac{\beta K_i / \tau_i}{(T_{s+1})(T_{s+1})} 
\]

where \(K_i\) is the controller proportional coefficient, \(\tau_i\) is the current regulator integral time constant, \(\beta\) is the current feedback coefficient, \(K_i\) is the rectifier amplification factor, \(R_a\) is the armature resistance, \(T_l\) is the motor electromagnetic time constant, \(T_{\Sigma e}\) equivalent small inertia group time constant, \(T_r\) is the rectifier lag time constant, and \(T_{\Sigma f}\) is the current filter time constant.

The vehicle obtains a corresponding sudden driving resistance in driving conditions, and this transient sudden-change signal causes the vehicle driving stability to change. The second-order system has acceptable anti-interference capability. The motor speed control system is calibrated to a typical second-order system that can effectively resist the role of sudden driving resistance. The speed control system uses PI control tuning parameters. Thus, the speed control loop open-loop transfer function is as follows:

\[
W_{op}(s) = \frac{K_n \alpha R_e (\tau_n s + 1)}{\tau_n \beta C_e T_{on} s^2 (T_{\Sigma e} s + 1)}
\]

\[
T_{\Sigma f} = 2T_{\Sigma e} + T_{on}
\]

where \(K_n\) is the speed regulator proportional coefficient, \(\alpha\) is the speed feedback coefficient, \(\tau_n\) is the speed regulator integral time constant, \(C_e\) is the back-EMF coefficient, and \(T_{on}\) is the speed filter time constant.

The differential time constant of the current regulator and speed regulator can be set according to Ziegler–Nicholas parameters. The first method selection is as follows:

\[
\begin{align*}
T_{d} &= 2T_{d1} \\
T_{d1} &= 2T_{d2}
\end{align*}
\]

where \(T_{d2}\) is the current loop equivalent lag time, and \(T_{d1}\) is the speed loop equivalent lag time.

3.2. Adaptive Fuzzy PID Control Design

Brushless DC motor, as the controlled object, includes the motor speed and current adaptive fuzzy PID control \[4\]. For example, in a speed loop, the controller inputs the error \(e\) and the error rate of change \(ec\) after the detected speed feedback value is compared with a given value. Suppose the initial value of PID parameter is \(k_{p0}, k_{i0}, k_{d0}\). The correction value \(\Delta K_p, \Delta K_i, \Delta K_d\) is obtained after defuzzification and superposed with the PID parameter value of the previous moment to obtain the moment PID control parameters according to the relationship between input variables \(e\) and \(ec\) and parameter \(k_p, k_i, k_d\) in the PID control and the fuzzy control rules. This process is repeated. Continuous testing \(e, ec\) and continuous adjustment of the control parameters online are performed until the model error \(e\) and error rate of change \(ec\) satisfy the system requirements, thereby achieving an adaptive control system.
According to Eqs. (7), (8), and (11), the initial parameters of the current regulator based on fuzzy PID control are:

\[ K_{p0} = \frac{T_i R_m}{2K_i \beta \sum n}, \quad K_{i0} = \frac{K_i}{T_i}, \quad K_{d0} = 2K_p \tau_d \]  

\[ K_{p0} = \frac{(h+1) \beta C T_m}{2h \alpha R_m \sum n}, \quad K_{i0} = \frac{K_i}{h T_m \sum n}, \quad K_{d0} = 2K_p \tau_d \]  

The motor parameters are \( k_{p0}=4, k_{i0}=3, k_{d0}=0.3 \). The domain of input \( e, ec \) and output \( \Delta K_p, \Delta K_i \) on the fuzzy set are \([-3,3]\), and the domain of \( \Delta K_d \) is \([-0.3,0.3]\). Mandani reasoning rules are used according to the actual demand. The fuzzy subsets of input and output are set to \{NB, NM, NS, Z, PS, PM, PB\} and expressed as \{negative, negative, negative, zero, positive, positive, positive\}. The triangular membership function with excellent resolution and high sensitivity is selected for a robust and practical fuzzy controller [10].

Similarly, according to (9), (10), and (11), the initial parameters of the speed regulator based on fuzzy PID control are:

\[ K_{p0} = \frac{(h+1) \beta C T_m}{2h \alpha R_m \sum n}, \quad K_{i0} = \frac{K_i}{h T_m \sum n}, \quad K_{d0} = 2K_p \tau_d \]  

The motor parameters \( \Delta K_{p0}=10, \Delta K_{i0}=0.9, \Delta K_{d0}=0.6 \) indicate that the input \( e, ec \) in the fuzzy set is \([-3,3]\), \( \Delta K_p \) is \([-9.9]\), \( \Delta K_i \) is \([-0.9,0.9]\), and \( \Delta K_d \) is \([-0.6,0.6]\). Mandani reasoning rules are also used. The fuzzy subset selected seven level divisions, and the input and output membership functions are triangular. \( e, ec \), and the output \( \Delta K_{p0} \) membership function are inputted as shown in Figures 3.

The correction coefficient \( \Delta k_p, \Delta k_i, \Delta k_d \) of the PID parameter is changed with \( e \) and \( ec \) according to the basic settings of the fuzzy controller, the experience of experts, the statistics of the historical data, which are based on the actual demand of the double closed-loop control system of the speed current, and according to the principle of adaptive fuzzy parameter setting [1], as shown in Figures 4–6.
4. Adaptive Fuzzy Controller Optimized by Genetic Algorithm

GA includes chromosome coding scheme, individual fitness evaluation, selection operation, cross operation, and mutation operation. The shape of the membership function is fixed to a uniformly distributed triangle, which is optimized by using GA to obtain the optimal control rules.

4.1. Coding scheme

To encode the fuzzy membership function, the abscissa of the three vertices of the membership function triangle is selected as the parameter to be optimized; that is, \{x_1, x_2, x_3, x_4, x_5\} is encoded, in which \(x_{\text{min}} < x_1 < x_2 < x_3 < x_4 < x_5 < x_{\text{max}}\). The parameters of the five membership functions of the system are expressed in Formula (14) using a 5-tuple \((s_1, s_2, s_3, s_4, s_5)\) with a length of \(5 \times 5 = 25\).

\[
x_i = x_{\text{min}} + \frac{s_i}{30}(x_{\text{max}} - x_{\text{min}}), i = 1, 2, 3, 4, 5 \quad 0 < s_1 < s_2 < s_3 < s_4 < s_5 < 30
\]  

(14)

4.2. Fitness Function

For effective system tracking, short rising time, small overshoot, and short transition time, the square term of the control output is added to the objective function, and the penalty function is introduced. The expression is shown in Equation (15) as follows:

\[
J = \int_0^\infty \left( w_1 |e(t)| + w_2 u^2(t) + w_3 |e(t)| \right) dt + w_4 \cdot t_r,
\]

(15)

where \(e(t)\) is the system error, \(u(t)\) is the controller output, and \(t_r\) is the rising time. \(w_1, w_2, w_3, w_4\) are the weights, and \(w_4\) is much larger than \(w_1\). When the value of the index function is small, its performance is better. The fitness function represents its inverse, and the expression is as follows:

\[
\text{fit} = \frac{1}{1+J}
\]

(16)
4.3. Genetic operators

The function of the choice operator is to select good individuals from the current generation and duplicate them into the next generation [9]. The fitness ratio method is used to set the fitness value of an individual. The probability that the individual is selected is obtained as follows:

\[
p_i = \frac{f_i}{\sum f_i}
\]  

(17)

where \( m \) is the size of the population, \( f_i \) is the fitness of the \( i \)th individual in the population, and \( p_i \) is the probability of the \( i \)th individual being selected.

Cross is the operation of two parent individuals being replaced and reorganized by the crossover probability in a certain approach to generate a new reorganization. The 25-bit membership function coding, with five variables, is divided into five groups, encoding 5 bits in each group; cross-exchange occurs between groups. First, the allele performs a genetic comparison with others. If the absolute value of the gene to be swapped is less than two, then the allele is allowed to swap. This condition can avoid sudden swaps in the control process. Unreasonable control rules and large oscillation of the control system occur due to these rules. The crossing probability \( p_c \) is 0.7.

Mutation operations randomly select one or more loci from the individual coding strings in the population and change the gene values of the loci according to the mutation probability to generate new individuals. Similar to the design of crossover operators, the same mutation operations for membership functions and rules are performed. For the coding of the 25-bit membership function, if the probability of mutation is less than 0.01 and the mutating loci plus 1 is still less than the latter, then the mutation is implemented. The designed mutating probability \( p_m \) is 0.01.

The design of adaptive fuzzy PID controller based on GA optimization is completed. The membership function is optimized by GA. For example, as shown in Figure 7, when \( e \) and \( ec \) are small, the base of the corresponding triangle is reduced. Thus, the recognition capability of the fuzzy subset and the control sensitivity is improved.

![Optimized input and output membership functions](image)

**Figure 7.** (a) \( e \) (b) \( ec \) Optimized input and output membership functions

5. Model Simulations and Analysis

The model is established and tested by using MATLAB/Simulink. The sampling time \( T \) of the simulation system is set at 0.0005 s. The prototype of a typical vehicle driving BLDC motor is used as a prototype of the motor. The basic parameters of the prototype are as follows: winding inductance \( L \) is 0.02 H; winding mutual inductance \( M \) is -0.067 H; damping coefficient \( B \) is 0.0002; total resistance \( R \) is 0.958Ω; motor rotor moment of inertia \( J \) is 0.005 kg•m\(^2\); pole pair number \( p \) is 1; counter electromotive force coefficient \( k_e \) is 0.382; rated speed \( n = 1,500 \) r/min; and motor rated voltage \( U \) is the standard 220 V. To verify that the GA optimized the adaptive fuzzy PID control algorithm loaded in the brushless DC motor simulation model, the dynamic performance is optimized, and the system is set in the no-load start into the steady state, with sudden load at \( t = 0.2 \) s \( T_L = 10 \) N•m, and the sudden load change is \( T_L = 5 \) N•m at \( t = 0.4 \) s. The speed and torque of the brushless DC motor are under the control of ordinary PID, fuzzy adaptive PID, and GA. The simulation results are shown in Figures 8 and 9, respectively.

The simulation graphs show that compared with ordinary PID control and fuzzy PID control at the reference speed of 1,500 r/min, the control system of the genetic optimization adaptive fuzzy PID control method maintains torque stability at start-up without causing a large turn moment impact. The system rapidly responds and returns to steady state when the load mutation occurs after a short period of overshoot. The stability error is small. Figure 10 shows that a sudden change in load...
torque ripple is mainly due to current commutation and current hysteresis controller frequent switching. The simulation comparison proves that the designed genetic predisposition adaptive fuzzy PID control method reduces the steady-state error of the speed and torque response of the control system significantly. The system adjustment time is also greatly reduced, and the torque overshoot has a significant effect.

The brushless DC motor model is integrated into a pure electric vehicle driving model and simulated by using Simulink. The vehicle parameters of the simulation are as follows: total vehicle mass of 2,380 kg, main reduction ratio of 3.852, transmission ratio of 1.667, tire radius of 0.269 m, rolling resistance coefficient of 0.013, and mechanical efficiency of 0.90. The simulation comparison results are shown in Figure 10.
The brushless DC motor model is integrated into a pure electric vehicle driving model and simulated by using Simulink. The vehicle parameters of the simulation are as follows: total vehicle mass of 2,380 kg, main reduction ratio of 3.852, transmission ratio of 1.667, tire radius of 0.269 m, rolling resistance coefficient of 0.013, and mechanical efficiency of 0.90. The simulation comparison results are shown in Figure 10. The simulation results show that the GA of the adaptive fuzzy PID control has the advantages of fast response time, small overshoot, strong anti-interference capability, and rapid recovery and stability. It has more applications in complex and changeable vehicle operating environments, as well as strong robustness and excellent adaptability.

6. Conclusions

The adaptive fuzzy PID control method is introduced in the dual closed-loop control of the motor speed and current, and GA is used to control the fuzzy controller in the membership function on the basis of an analysis of the permanent magnet brushless DC motor to optimize and improve the robustness of the fuzzy controller. MATLAB/Simulink is used to build, control, and test the model. Experimental results show that the motor control system based on GA with adaptive fuzzy PID control has good adaptability in a complex and changeable vehicle operating environment and has high anti-interference capability.

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