PMSM speed control method based on Kalman filter and dynamic fuzzy control in electric vehicle

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Abstract. Electric vehicles are widely used today, however, the phenomenon of sticking and shaking often occurs during starting, crawling and shifting. The cause of this phenomenon from the perspective of motor control was analyzed in this paper. In view of the disadvantages of low measurement accuracy of position sensor and traditional PID control, a dynamic fuzzy control speed control system based on Kalman filter optimal measurement was proposed. The principle of the system is simple, with good dynamic and static performance, which improves the accuracy of vehicle starting, crawling and gear shifting, and shortens the adjustment time.

1. Introduction

At present, the society strongly advocates energy saving and emission reduction. Electric vehicle has broad prospects because of its pollution-free, high energy utilization, low noise, simple structure and convenient maintenance. Permanent magnet synchronous motor (PMSM) is widely used in electric vehicles because of its high torque inertia ratio, high power density, high efficiency and good maintainability[1]. For electric vehicles, starting crawling and shifting often require the motor system to work in the speed control mode [2]. Aiming at the problem of poor anti-interference ability and inadequate precision of motor in complex operating environment, scholars at home and abroad have done a lot of research on the control method of PMSM. The rule-based control method is simple, feasible and easy to calculate, but its adaptability is poor [3-4]; the general PID control method can not meet the control performance requirements of dynamic response and stability under the condition of complex system and variable load [5]; the fuzzy PID control method does not need accurate modeling, and can solve general non-linear problems, but the control system Expert experience is highly demanded. Some artificial intelligence-based algorithms are also preliminarily used in the control system of automotive motors. However, for complex systems with serious uncertainties, there are still problems of large steady-state error and low steady-state accuracy [6-7]. In view of the deficiencies of conventional PID control and traditional fuzzy algorithm in motor control, Kalman filter is innovatively used to optimize the feedback of position sensor to reduce errors [8], and combined with the control idea of dynamic adjustment of PID coefficient by fuzzy algorithm [9], in the operation of PMSM of electric vehicle according to the actual negative of crawling and shifting. When load is changing, automatic correction of control coefficient works to meet the performance requirements of the system [10]. The control method is simple and applied to PMSM of electric vehicle. The double closed-loop control system of speed and current is established, which makes the motor control response fast and overshoot small, optimizes the motor control accuracy, and achieves accurate control of vehicle driving.
2. Principle and mathematical model of PMSM

PMSM has the advantages of simple structure, reliable operation and good speed control performance. However, PMSM is a highly coupled nonlinear complex system, so it is usually simplified in research [11]. Assuming that PMSM is an ideal motor, ignoring the saturation of the core of the motor, ignoring the armature reaction and symmetrical three-phase windings, and ignoring the loss caused by hysteresis and eddy current, its stator voltage equation in the synchronous rotating coordinate system d-q can be expressed as follows:

\[ u_d = R_i_d + L_i_d \frac{di_d}{dt} - w_e L_q i_q \]  
\[ u_q = R_i_q + L_i_q \frac{di_q}{dt} - w_e (L_d i_d + \psi_f) \]

where \( u_d \) and \( u_q \) are respectively the d-q axis component of stator voltage, V. \( i_d \) and \( i_q \) are respectively the d-q axis component of stator current, A. R is the stator resistance, \( \Omega \); \( w_e \) is the rotor electrical angular velocity, rad/s; \( L_d \) and \( L_q \) are the d-q axis inductance components respectively, H; \( \psi_f \) is the permanent magnet flux linkage, Wb.

3. Analysis of climbing and shifting problems

For electric vehicles, climbing and shifting belong to the problem of speed regulation. When the system works in the starting crawling condition, the change of mechanical speed is very stable and slow. In fact, the calculation period of electricity is very fast. If ordinary PID speed regulator is used, serious integration saturation will occur in a short time due to the introduction of integration links, resulting in large overshoot and long-term oscillation. For the car body, there will be obvious jitter. Similarly, when the system works in gear shifting, the output torque of the motor suddenly increases/decreases. Due to the inertia of the machine and the hysteresis of PID regulation, the ordinary PID speed regulator is difficult to adapt, which will force the motor speed to change rapidly. The system will inevitably have an overshoot link. During gear shifting, overshoot will produce obvious sense of standstill and noise of gear meshing.

In the electric vehicle system. The control process of crawling and shifting is as follows: the vehicle controller sends the speed instruction to the motor controller, and the motor controller collects and calculates the corresponding speed information through position sensor (resolver) and feeds back to the vehicle controller through CAN bus. Because of the structure characteristics of traditional sensors, the error of rotating straight line is not in the closed loop, which affects the accuracy of displacement detection. The inertia of mechanical system is large. At the same time, it will be affected by electromagnetic noise. The measurement is not accurate enough. For electric vehicles, it is required that the speed measurement can still be controlled stably in bad working environment without jittering or slipping.

4. Kalman filter optimization

4.1 Principle of Kalman filtering

In the motor system, the state variable disturbed by noise is a random variable, and it is impossible to measure the exact value. However, a series of observations can be made on it, and a set of observations can be used to estimate it from a statistical point of view. Kalman's recursive optimal
estimation theory uses state space description method and recursive form in the algorithm. Kalman filter can deal with multi-dimensional and non-stationary stochastic processes, approaching the real value as accurately as possible. At present, Kalman filter is mostly used for parameter identification, space displacement tracking and even image recognition. Permanent magnet synchronous motor (PMSM) displacement sensor also receives the limitation of noise and mechanical performance, and the measurement is not accurate [12]. This paper proposes a dynamic speed regulation system based on Kalman filter optimal measurement to expand its new application scenario.

Figure 2. Algorithm flow chart of Kalman filter optimization measurement
Kalman filtering is an iterative process. Each iteration is divided into two steps: prediction and correction. The prediction is to predict the system state and error covariance at this time according to the results of previous iteration, namely, x(k-1|k-1) and P(k-1|k-1), x(k|k-1) and P(k|k-1) are obtained. the flow chart is shown in figure 2. above.

4.2 Optimization results of position sensor
The results show that the Kalman optimization algorithm is simple and effective in eliminating the noise interference of linear systems. It only needs the current measurement value and the estimated value of the previous sampling period to estimate the state, and is closer to the real value of the measurement, which improves the accuracy of the system.
5. Dynamic fuzzy PID algorithm
The speed loop is improved, and the input of the controller is the error \( e \) and the error change rate \( e_c \) after the detected speed feedback value is compared with the given value. Setting the initial value of PID parameters, according to the relationship between input variables \( e, e_c \) and parameters in PID control and fuzzy control rules, the revised value is obtained after deblurring, and the revised value is superimposed with the PID parameter value of the previous moment, then obtaining the PID control parameters of this moment.

![Figure 5.Block diagram of dynamic PID regulator for fuzzy control](image1)

![Figure 6. Membership function of e and ec](image2)

![Figure 7. Membership function of Δkp](image3)

![Figure 8. Output surface on domain of Δkp](image4)

![Figure 9. Output surface on domain of Δki](image5)

![Figure 10. Output surface on domain of Δkd](image6)

6. Simulation and analysis
The model is built and tested in the MATLAB/simulink. Kalman filter and dynamic fuzzy algorithm are added to the traditional PMSM double-loop speed regulation system [13-14]. The sampling time \( T \) of the simulation system is set at 0.000 005s. The parameters of the motor are shown in the table below.

| Parameter names             | Values   |
|----------------------------|----------|
| Sampling time              | 0. 5 ms  |
| Winding self-induction     | 0.02 H   |
| Winding mutual inductance  | -0.069 H |

Table 1. Basic parameters of PMSM in electric vehicle
Damping factor 0.0002
Total resistance 0.948Ω
Rotary inertia of motor rotor 0.005 kg·m²
Back EMF coefficient 0.385
Rated speed 1500 r/ min
Polar logarithm 1

Figure 11. Control simulation diagram of PMSM in electric vehicle

Figure 12. Simulated speed response diagram at shifting

Figure 13. Kalman filter and dynamic fuzzy control simulation diagram at shifting

Figure 14. Simulated speed response diagram at climbing a slope

Figure 15. Kalman filter and dynamic fuzzy control simulation diagram at climbing a slope
7. Conclusion
Aiming at the shortcomings of direct traditional PID control and fuzzy control, the problems and reasons of electric vehicle when climbing and shifting were analysed in this paper, and a dynamic fuzzy control speed regulation system based on Kalman filter optimal measurement was put forward. The improved method combines the advantages of strong robustness of the fuzzy control system and high accuracy of Kalman filter optimization, which makes the system have good dynamic and static performance. On this basis, a MATLAB/simulink model is built. The results show that the improved control strategy of PMSM has the characteristics of fast response, small torque ripple, short transition period and high accuracy.

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References
[1] WANG Shu-mei. (2017) Simulation of slow sliding mode observer in brushless DC motor. Measurement & Control Technology, 36: 89–91.
[2] GAO Bing-zhao, HONG Jin-long, CHEN Hong. (2017) Drivability control of automotive drivetrain. Control Theory & Applications, 7:849–866.
[3] Ehsani Mehrdad, Gao Yimin, Emadi Ali. (2010) Basic principles, theory and design of modern electric vehicles, hybrid electric vehicles and fuel cell vehicles. Machinery Industry Press, Beijing.
[4] Song Z, Jianqiu L I, Ouyang M, et al. (2013) Rule-based fault diagnosis of hall sensors and fault-tolerant control of PMSM. Chinese Journal of Mechanical Engineering, 26:813-822.
[5] LIU Yan-cheng, REN Jun-jie, WANG Ning. (2015) Research of sliding mode observer for permanent magnet synchronous motor based on the synchronous rotating frame. Electric Machines and Control, 19:36–44.
[6] Jovid. (2008). Application of fuzzy control based on particle swarm optimization in BLDCM. Micromotor, 41:90–92.
[7] Omar Aguilar-Meja, Raul Sosa-Cortes, et al. (2018) Speed Control of PMSM using nature-inspired algorithms. IEEE Latin America Transactions, 16: 677–685.
[8] JIANG Hao-nan, CAI Yuan-li. (2018) Robust Gaussian-sum ensemble Kalman filter and its application in bearings-only tracking. Control Theory & Applications, 35:129–136.
[9] XIAO Na-chuan, ZOU Li, ZHOU Zhi. (2015) Research of electric vehicle motor controller based on fuzzy PID algorithm. Chinese Journal of Power Sources, 1:144–146.
[10] NI You-yuan, LIU Yue-bin. (2019) Analytical modeling and analysis of permanent magnet machine with combined magnetic poles. Electric Machines and Control, 23: 52–62.
[11] Dursun, M., Boz, A.F., Kale, M., Karabacak, M. (2018) Sensorless control application of PMSM with a novel adaptation mechanism. Neural Computing and Applications, 29: 87–103.
[12] YUAN Lei, HU Bingxin, WEI Keyin, et al. (2016) Control Principle and MATLAB simulation of modern permanent magnet synchronous motor. Beijing University of Aeronautics and Astronautics Press, Beijing.
[13] WANG Feng-yuan, XIE Xian-zi, HE Jian-yong, et al. (2015) Electric Vehicle Motor Double Closed Loop Speed Control Strategy of Difference. Computer Simulation, 12: 107–112.
[14] WANG Jun, FENG Nenglian, et al. (2016) Research on a speed regulating system for the brushless DC motor using fuzzy and PI controller. Journal of Anhui Agricultural University, 43: 662–666.