Adaptive Parameter Determination Method of Synchronous Motor Digital PI Regulator

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Abstract. The parameter adaptation of digital PI regulator of synchronous motor has great influence on the production and use of current electric and mechanical equipment. In order to optimize the effect of synchronous electric digital regulator, a method of parameter adaptive determination of digital PI regulator of synchronous motor is proposed, which improves the process of setting parameters in continuous domain. The adaptive parameters of digital PI regulator of synchronous motor are collected and analyzed by discretization method. The sampling time and phase angle lag parameters caused by zero order maintainer are eliminated. The mathematical model of parameters of digital PI regulator of synchronous motor is established, and the discrete model diagram of closed-loop synchronous motor is obtained. The time domain performance index is converted into the open loop frequency domain characteristic quantity by engineering experience and the PI regulator parameters are calculated analytically in the domain. Simulation results show that the adaptive determination method of digital PI regulator of synchronous motor meets the design requirements. The overshoot is less than 5% and the adjustment time is about 1.92 s. The research shows that the method can provide reference for the parameter setting of digital PI regulator of synchronous motor.

Keywords: Synchronous motor · Regulator · Self-adaptive

1 Introduction

In recent years, PI regulator parameter adaptation has made great progress both in theory and technology, and has become a very active and fruitful branch in the field of automatic control. Its typical application involves many aspects of production and life. At present, the level of industrial automation has become an important symbol to measure the modernization level of all walks of life. The development of parameter adaptation of synchronous motor digital PI regulator has also gone through three stages: classical control theory, parameter adaptation theory of synchronous motor digital PI regulator and intelligent control theory. Automatic control can be divided into open-loop control system and closed-loop control system. Synchronous motor has the advantages of high

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power factor, high efficiency, high power density and wide speed range, which has been widely used in industry. At the same time, synchronous motor control technology is also constantly improving and perfecting [1]. The double closed-loop vector control synchronous motor based on digital PI regulator is easy to realize and has good control effect, which has been widely used in engineering. In order to better guarantee the operation effect of synchronous motor, the optimization research of adaptive parameter determination method of synchronous motor digital PI regulator is proposed to obtain higher synchronous motor acceleration, Stable torque can be obtained, so it is widely used in high-performance speed control synchronous motor, and the most commonly used control method is double closed loop PI regulation [2]. At present, there are many methods to adjust the parameters of PI regulator, such as adaptive PID, fuzzy control, etc. the control design of these methods is too complex. Based on this, according to the classical engineering design method of PI regulator, combined with the characteristics of digital control synchronous motor, the high performance design requirements of current loop and speed loop are optimized. In this paper, a PI parameter design technique for double closed-loop control of synchronous motor is proposed, which fully considers the problems of synchronous motor loop width, sampling period, motor time constant, regulator parameters and their constraints. The parameter adaptive accuracy of digital PI regulator of synchronous motor is verified by experiment. The experiment proves that the parameter adaptive determination method of digital PI regulator of synchronous motor has high application value [3].

2 Synchronous Motor Digital PI Controller Parameter Self-adaptive

2.1 Parameter Identification Analysis of Synchronous Motor Digital PI Regulator

Multivariable parameter tuning of synchronous motor is very complicated, but its theory research is very fast. Based on the research results, the optimization design of digital PI controller parameters is proposed. Combined with the current popular method of multi-variable PID parameter tuning, the multi-variable data of correction factor and Hu Jinxing PI regulation, assume the discrete form of multi-variable PI regulator used in the closed loop of synchronous motor is as follows:

$$u(k) = K_P e(k) + K_I \sum_{i=0}^{k-1} e(i) + K_D[e(k) - e(k-1)] \tag{1}$$

The PI regulator in frequency domain is used to identify the parameters of the simple control object, and the PID time domain measured data is used to identify the parameters. There are many parts in the synchronous motor controlled by the synchronous wind turbine converter and its regulator, which can easily affect the parameter identification effect of the synchronous motor digital PI regulator. Therefore, the parameter identification law of the synchronous motor digital PI regulator is specifically studied based on the directly measurable input/output data in time domain. The identification law of the synchronous motor digital PI parameter is shown in Fig. 1:

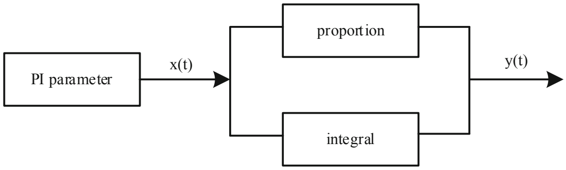


Fig. 1. Identification law of digital PI parameters for synchronous machines

It is difficult to adjust the PI parameters for the multi-variable synchronous motor with strong coupling, and the control parameters can only be compromised between the coupling parameters. Some data (digital quantity) of the actual input and output signals are collected at the communication interface of the PI regulator. If the input value is *x* (*t*), the output value is *y*(*t*), and *d* is a digital quantity, and the proportional coefficient k_p and the integral coefficient k_I are the parameters to be identified, then:

$$y(t) = u(k)K_{\mathrm{P}}\left[x(t) + \frac{1}{K_1}\int_0^t x(t)\mathrm{d}t\right] \tag{2}$$

Set the sampling interval to *t*. According to the sampling theorem, when the sampling frequency of data is very high, there is a discrete form:

$$y(k) = K_{\mathrm{P}}\left[x(k) + \frac{1}{K_{\mathrm{I}}}\Delta t_s \sum_0^k x(k)\right] \tag{3}$$

When the input values of successive test points are unchanged, $x(k) = x(k-1) = x(k-2) = \cdots$, such as:

$$y(k)' = K_{\mathrm{P}}\left[x(k) + \frac{1}{K_{\mathrm{I}}}\Delta t_{\mathrm{S}} \sum_0^k x(k)\right] = K_{\mathrm{P}}\left[x(k-1) + \frac{1}{K_{\mathrm{I}}}\Delta t_{\mathrm{S}} \sum_0^{k-1} x(k-1)\right] + \frac{K_{\mathrm{P}}}{K_{\mathrm{I}}}x(k)\Delta t \tag{4}$$

$$y(k-1) = K_{\mathrm{P}}\left[x(k-1) + \frac{1}{K_{\mathrm{I}}}\Delta t_0 \sum_0^{k-1} x(k-1)\right] \tag{5}$$

The classical PI regulator directly controls the controlled object in closed loop, and the three parameters K_p, K_i, K_d of the regulator are adjusted online. According to the operation state of the synchronous motor, the parameters of the PI regulator are adjusted in order to achieve the optimization of some performance index, so that the output state of the output layer neuron can pass the self-learning and weighting coefficient of the three adjustable parameters K_p, K_I, K_d of the PI regulator Adjust the output to correspond to the parameters of PI regulator under some optimal control law[4–6]. When the input of two consecutive measuring points is 0 and the input and output of subsequent measuring points are respectively x(j), y(j), there are:

$$y(j-1) = K_{\mathrm{P}}\left[x(j-1) + \frac{1}{K_{\mathrm{I}}}\Delta t_0 \sum_0^{j-1} x(j-1)\right] = \frac{K_{\mathrm{P}}}{K_1}\Delta t_0 \sum_0^{j-1} x(j-1) \tag{6}$$

The above formula determines the structure of multivariable PI regulator. Each coefficient matrix is composed of coarse adjustment part and adjustable correction factor (fine adjustment) which are determined by the characteristics of the object [7]. The coarse adjustment part can be determined by synchronous motor identification, and the expert correction method is used to adjust the correction factors online. The relationship between output step response mode and correction factor γ_I, ε_I, δ_I is described by production rule, and these modes are characterized by decay rate, overshoot, rise time and vibration period. A unified correction formula for various modes is proposed:

$$\begin{cases} P(n) = P(n-1)\left[1 + \mathrm{sgn}\left(\sum_{i=1}^{1} swe_i\right)e^{-(n+1)/2}\right] \\ swe_i = s_i \times w_i \times e_i \end{cases} \quad (7)$$

Further, the speed control structure block diagram of the motor is built according to the identifiability calculation method and steps, as shown in Fig. 2.

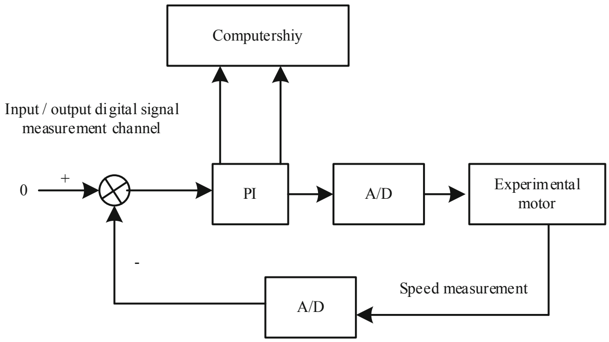


Fig. 2. Structure block diagram of PI data measurement

Furthermore, the gradient method is used to adjust the parameters of PI regulator online through weights. When the coupling of synchronous motor is serious, the multivariable PI regulator structure composed of a single motor is needed. In order to achieve better control effect of PI regulation, it is necessary to adjust the three control functions of proportion, integral and differential to form the relationship of mutual coordination and mutual restriction in the control variables. This relationship is not necessarily a simple "linear combination", and the best one can be found from the infinitely variable nonlinear combination [8, 9]. With the ability of arbitrary nonlinear expression, the optimal PI regulation can be realized by learning the performance of synchronous motor, so that the three parameters of PI regulator can be adjusted to the optimal parameters online, and the method of parameter self-learning of PI regulator is established [10].

2.2 Adaptive Control Algorithm of Synchronous Motor

According to the control theory of synchronous motor, synchronous motor has sinusoidal back EMF waveform, and its stator voltage and current should also be sinusoidal [11].

Assuming that the motor is linear, its parameters do not change with temperature and other external conditions, ignoring the hysteresis and eddy current loss, the rotor has no damping winding [12]. According to the stator voltage vector equation of synchronous motor in rotating coordinate system in two-phase winding, the stator voltage equations of two components of synchronous motor on shaft are obtained

$$\begin{bmatrix} V_d \\ V_\theta \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} p & -\omega_z \\ \omega_r & p \end{bmatrix} \begin{bmatrix} \Psi_d \\ \Psi_q \end{bmatrix} \tag{8}$$

R_s and R_0 are the components of stator voltage vector $\begin{bmatrix} I_d \\ I_q \end{bmatrix}$ of synchronous motor; ω_z is the angular velocity of rotor rotation; ω_z is the component of field oriented control value $\begin{bmatrix} \Psi_d \\ \Psi_q \end{bmatrix}$ of synchronous motor. As long as the actual I_d, I_q is equal to the given Ψ_d, Ψ_q, it meets the requirements of actual control [13]. In the actual control, the current injected into the motor stator and detected from the stator is three-phase current, so the coordinate transformation must be carried out [14]. Because the coordinate system is the rotating coordinate system of the stator on the motor rotor, in order to realize the coordinate transformation, the position of the motor rotor must be detected in real time in the control, and the double closed-loop structure of synchronous motor field oriented control is constructed:

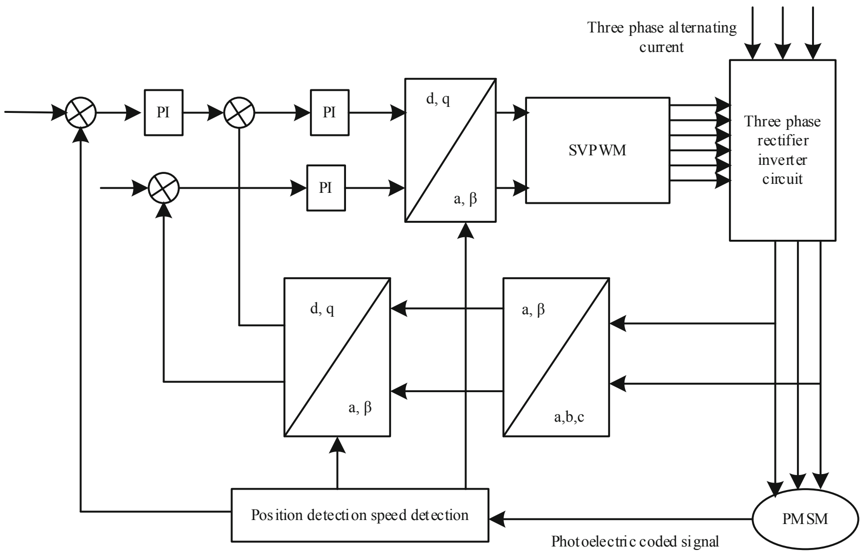


Fig. 3. Double closed loop control of synchronous motor field orientation

As shown in the Fig. 3, the design starts from the inner ring and gradually expands outward. Starting from the current loop, the current regulator is designed. The current loop is regarded as a link in the speed regulating synchronous motor, and then the speed loop is designed. The function of the current loop is to improve the speed of the synchronous motor, restrain the internal interference of the current loop, and limit the maximum current to ensure the safe operation of the synchronous motor [15]. The function of speed loop is to enhance the ability of synchronous motor to resist load disturbance and restrain speed fluctuation. In the PI regulator parameter tuning, the data is collected in the offline working mode, so when the synchronous motor structure changes, the data can not be updated online, so it is necessary to re collect data for tuning [16]. This paper presents a feasible method which can be better extended to the nonlinear synchronous motor, that is to expand the original PI regulator off-line database. At each sampling time, the data of the current process is added to the original offline database, so the data node of the current PI regulator will be covered by the extended database. Then, at each sampling time, the extended database can be used to adjust the parameters of the regulator [17]. In order to achieve this goal, the distance definition is used to select the closest I group of data which is consistent with the current process conditions in the expanded database

$$d_i = \|x(k-1) - x_i\| \tag{9}$$

Among them, $x_i = [y(i)u(i)]^T$ is a group of I / O data of the current data node. In the current database, m x which is closest to X $(k-1)$) are selected as the relevant data of the current PI regulator database to set the regulator parameters at the current sampling time. When the PI regulator database is further updated by the last data node, the above design process is repeated [18]. When the structure of synchronous motor changes, it is unreasonable to reset the pseudo gradient estimation value to the initial value of pseudo gradient. The pseudo gradient estimation value of synchronous motor is reset to the adaptive parameter of PI regulator, and the pseudo gradient value is reset by using the database. But at this time, the database is composed of m groups of synchronous motor I/O data close to the current data node, so as to ensure the PI regulator parameters Adaptive processing effect [19].

2.3 Test of PI regulator's Self-adaptation

On the basis of parameter tuning of multivariable PI regulator based on genetic algorithm, the operation parameters of PI regulator are predicted based on particle swarm optimization algorithm, and the controlled multivariable synchronous motor is transformed into several multi input and single output sub synchronous motors, thus the control problem of multivariable synchronous motor is transformed into several single output sub synchronous motor control problems The prediction model predicts the output of the sub synchronous motor, and then uses the particle swarm optimization algorithm to adjust the parameters of the PI regulator.

As shown in the Fig. 4, the feedback of the hidden layer nodes of the feedforward network to the nodes of the previous layer or the self-feedback to the nodes of this layer belongs to local connection recursion. In the application, firstly, it simplifies the network structure of multilayer feedforward network and reduces the number of nodes, thus overcomes the problem that the dynamic modeling of multilayer feedforward network turns into static modeling. Real-time control is one of the key problems in the application

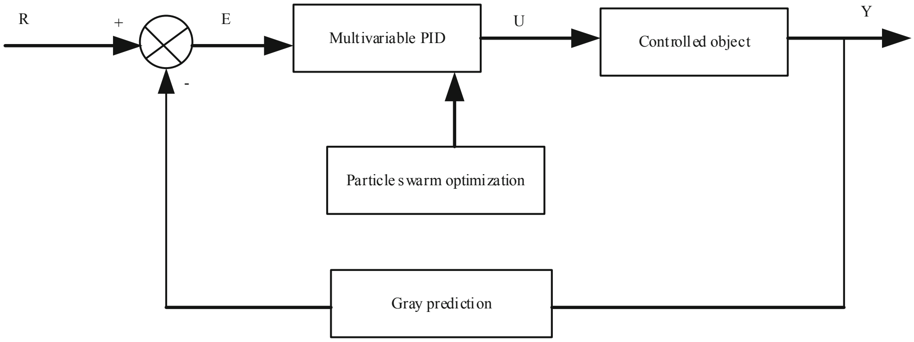


Fig. 4. Synchronous motor PI controller parameter control structure

of PI controller for synchronous motor. Therefore, the PI controller needs less network computation and is more suitable for real-time control and adaptive processing. Diagonal recursion is the simplest local interconnection recursion from the structure of synchronous motor PI regulator. It is easy to construct training algorithm, and the hidden layer node has self-feedback connection. Compared with the standard feedforward network, DRNN has the same input/output and implicit cell, but the implicit cell of DRNN has self-feedback. The dynamic mapping and memory function of DRNN is realized by recursive neuron capturing the dynamic characteristics of synchronous motor in the inner feedback loop. Compared with fully connected RNN implicit cells, there is no mutual information exchange between them, so the model is greatly simplified and the adaptive speed is guaranteed. In order to implement complex control conveniently in practical engineering, a high order regulator approach using multivariable PI regulator is presented. By adjusting a design parameter reflecting closed-loop, robust stability and time-domain performance of synchronous motor, multivariable PI regulator can be obtained. The main idea is to design a full order H regulator for the original synchronous motor by loop forming H method, and then reduce the order of the regulator on the basis of the closed-loop synchronous motor. Based on the control structure shown above, the standard adaptive form of the multivariable PI regulator is as follows:

$$D(s) = \frac{U(s)}{E(s)} = \begin{bmatrix} d_1(s) & & & \\ & d_2(s) & & \\ & & \ddots & \\ & & & d_n(s) \end{bmatrix} \tag{10}$$

The multi-variable PI regulator tuned by the above method is very simple, which is equivalent to selecting the parameters of each loop, and the tuned parameters are high efficient and clear.

3 Analysis of Experimental Results

In order to verify the dynamic and steady-state performance of the proposed method, it is proved that the proposed method is effective. In order to ensure the accuracy of the experiment and avoid the difference of the experimental results under the influence of different experimental environment and parameters, the experimental parameters are first standardized, and the specific parameters are shown in the Table 1.

Table 1. Operation parameter specification of synchronous motor

Parameter	Numerical value
Rated power/kW	7.5
Rated cabinet TL/N·m	17.5
Direct axis inductance L d/H	0.010 96
Quadrature axis inductance Lq/H	0.012 44
Polar logarithm p	5
Moment of inertia J/(kg · m^2)	0.285
Friction coefficient B	0.000 3
Rotor flux amplitude Ψf/WB	0.233 9
Winding resistance R/Ω	0.29
Sampling frequency/Hz	5000
Current loop regulation period T/S	0.000 2
Speed ring regulation cycle T/S	0.004

Because the PI regulator always operates under certain interference conditions, in order to verify the authenticity of PI parameter identification results, interference test is applied to the experimental platform, and the test site is selected in the EMC laboratory of automation equipment of State Grid Corporation of China (the designated unit of power equipment access test). In the test, pulse group interference test and oscillation wave interference test are carried out, which are the tests that must be passed to test the power control device. Based on this, the traditional method and the experimental results of this method are compared and recorded. In the experiment, the input and output data of IP operation under these two conditions are measured respectively. The restoration results of output data under the condition of pulse group interference test are shown in the table. The restoration results of output data under the condition of oscillation wave interference test are shown in the Tables 2 and 3.

In the process of experiment, the result of data recovery test is the same as that of the test without interference, and the calculated value of individual data is different from the measured value, because of the program setting of digital PI. Based on theoretical analysis and several prototype experiments, 4 pairs of pole surface mounted synchronous motor with 1.1 kW, 220 V, 200 Hz, rated speed of 3000 rgrain, rated torque of 3.5 $n \cdot m$ and rated current of 3 A are selected. The parameters are as follows: stator resistance 2.875 Q, $l = 8.5$ MH; moment of inertia 0.000 8 kg · m^2; PWM wave carrier frequency 5 kHz, current loop filtering time 40 PS, speed loop filtering time 2 ms. According to the above PI regulator parameter design method, the proportional parameter k_0 of current loop is 17.708, the integral parameter k_1 is 5989.58; the time constant r of speed loop is

Table 2. Comparison of calculated output and actual output under the condition of pulse group interference under the traditional method

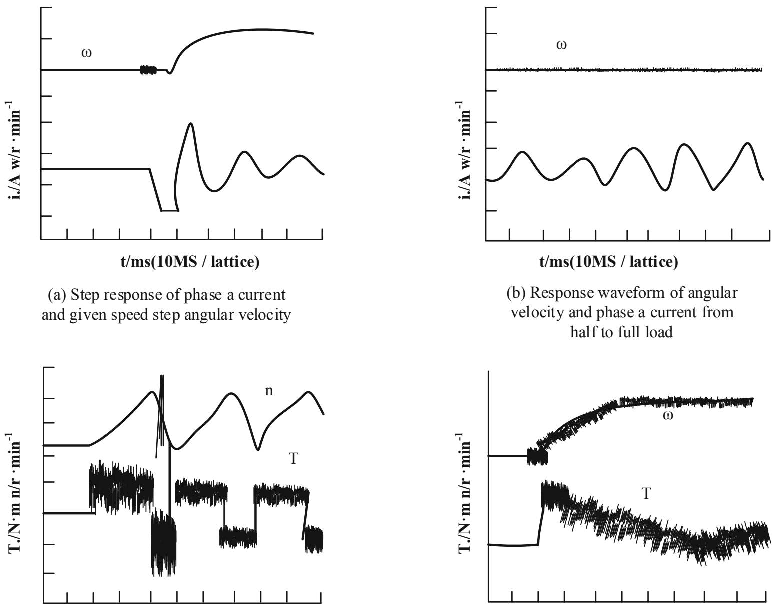
Serial number	input	Actual output	Calculation output	Is it equal
0	0.000	105.175		
1	0.000	104.182		
2	−0.025	111.170	142.106	yes
3	−0.025	102.190	142.101	No
4	0.010	131.156	151.103	Yes
5	0.010	124.570	151. 105	No
6	0.010	133.082	150. 107	No
7	0.030	126.045	161. 103	Yes
8	−0.035	131.026	139.107	No
9	0.010	105.500	155.105	Yes
10	0.010	105.052	154.103	Yes

Table 3. Comparison between calculated output and actual output under the condition of pulse group interference

Serial number	input	Actual output	Calculation output	Is it equal
0	0.000	185.181		
1	0.000	185.181		
2	−0.025	184.176	184.176	Yes
3	−0.025	184.171	184.171	Yes
4	0.010	185.573	185.573	Yes
5	0.010	185.575	185.575	Yes
6	0.010	185.577	185.577	Yes
7	0.030	186.383	186.383	Yes
8	−0.035	183.776	183.776	Yes
9	0.010	185.578	185.578	Yes
10	0.010	185.580	185.580	Yes

0.09, the proportional parameter k_n is 0.023. The waveform obtained in the experiment is shown in Fig. 5

Because the digital quantity of data in the experiment is directly connected to the computer through the communication interface, the accuracy of data acquisition is high. Using this data can accurately calculate a and b, and can accurately identify the parameters of PI regulator even under interference conditions. This experiment provides a



(a) Step response of phase a current and given speed step angular velocity

(b) Response waveform of angular velocity and phase a current from half to full load

(c) Response waveform of speed from 0 to 2000 R / min, speed and load torque

(d) The response waveform of speed and torque with given speed step of 2000 R / min

Fig. 5. Analysis of experimental results

method reference for high precision acquisition of input and output digital signals. There are many PI regulators in the control of synchronous motor. In the study of parameter identification of synchronous motor, the given PI regulator parameters can be taken as known conditions, which greatly simplifies the complexity of the problem. The results show that the regulator parameters designed by the above method can well meet the control performance of synchronous motor.

4 Conclusion

The method of PI regulator parameter tuning is studied, which includes two aspects. On the one hand, the single variable PI parameter tuning is studied, including the PI parameter tuning using genetic algorithm, wavelet and linear matrix inequality method in robust control theory. The specific design steps are given. On the other hand, the online tuning method of multivariable PI parameters is studied, and the main methods of multi-variable PI parameters tuning and the specific design of the algorithm are described. On the basis of diagonal recursion, the quasi diagonal recursion multivariable PI parameters tuning is proposed. On the basis of analyzing the mathematical model of synchronous motor, the driving model of synchronous motor with rotor field oriented vector control is established Dynamic synchronous motor model. Aiming at the double closed-loop structure of full digital high-power synchronous motor with field oriented control. The transfer function models of current loop and speed loop are established. According to the engineering design method of PI regulator, a design criterion and method of control parameters of digital PI regulator are given. The experimental results show that the adaptive parameter determination method of synchronous motor digital PI regulator achieves good control effect and has certain application value.

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References

1. Ashok, R.B., Kumar, B.M.: Comparative analysis of BLDC motor for different control topology. Energy Procedia **117**(11), 314–320 (2017)
2. Roy, R., Prabhakar, K.K., Kumar, P.: Core-loss calculation in different parts of induction motor. IET Electr. Power Appl. **11**(9), 1664–1674 (2017)
3. Martinez, J., Belahcen, A., Muetze, A.: Analysis of the vibration magnitude of an induction motor with different numbers of broken bars. IEEE Trans. Ind. Appl. **53**(3), 2711–2720 (2017)
4. Tutaev, G.M., Bobrov, M.A., Gulyaev, I.V.: Evaluation of the energy characteristics of an asynchronous inverter-fed induction motor at different approximations of the magnetization curve. Russ. Electr. Eng. **88**(6), 321–325 (2017)
5. Morosato, F., Traina, F., Cristofolini, L.: Effect of different motor tasks on hip cup primary stability and on the strains in the periacetabular bone: an in vitro study. Clin. Biomech. **70**(11), 137–145 (2019)
6. Jianqiu, L.: Construction of real-time interactive mode-based online course live broadcast teaching platform for physical training. Int. J. Emerg. Technol. Learn. (iJET) **13**(06), 73 (2018)
7. Fu, W., Liu, S., Srivastava, G.: Optimization of big data scheduling in social networks. Entropy 21(9), 902 (2019)
8. Liu, S., Bai, W., Zeng, N., et al.: A fast fractal based compression for MRI images. IEEE Access **7**(12), 62412–62420 (2019)
9. Liu, Q., Chen, Z.Y., Yang, S.F., et al.: Magnetic properties of pure iron with respect to different C/Si ratios and grain sizes. Mater. Sci. Forum **913**(10), 653–660 (2018)
10. Nguyen, M.Q., Dario, S., Malec, D., et al.: Environmental assessment and dielectric performances of the secondary electrical insulation in low voltage motors impregnated by different techniques. Engineering **9**(10), 860–873 (2017)
11. Kumar, H., Tengli, P.N., Mishra, V.K., et al.: Synthesis and catalytic activity of Cu–Cr–O–TiO 2 composites for the thermal decomposition of ammonium per-chlorate: enhanced decomposition rate of fuel for solid rocket motors. RSC Adv. **7**(21), 12486–12495 (2017)
12. Cao, R., Lu, M.: Investigation of high temperature superconducting linear flux-switching motors with different secondary structures. IEEE Trans. Appl. Superconduct. **30**(4), 1–5 (2020)
13. Chen, Y., Cai, T., Zhu, X., et al.: Analysis and design of a new type of less-rare-earth hybrid-magnet motor with different rotor topologies. IEEE Trans. Appl. Superconduct. (2020)
14. Huthaifa, F., Lorenz, R.D., Eigo, T., et al.: Investigation of different servo motor designs for servo cycle operations and loss minimizing control performance. IEEE Trans. Ind. Appl. **54**(6), 5791–5801 (2018)
15. Han, S., Liu, C., Sun, X., et al.: Investigation of static characteristics in six-phase switched reluctance motors under different winding connections. IEEE Access **7**(11), 71174–71184 (2019)

16. Terao, Y., Akada, W., Ohsaki, H.: Design and comparison of interior permanent magnet synchronous motors using different bulk superconductor arrangements. IEEE Trans. Appl. Superconduct. **29**(5), 1–5 (2019)
17. Sun, X., Diao, K., Lei, G., et al.: Study on segmented-rotor switched reluctance motors with different rotor pole numbers for BSG system of hybrid electric vehicles. IEEE Trans. Veh. Technol. **68**(6), 5537–5547 (2019)
18. Huang, X., Qian, Z., Tan, Q., et al.: Suppressing the thrust ripple of the permanent magnet linear synchronous motors with different pole structures by setting the modular primary structures differently. IEEE Trans. Energy Convers. **33**(4), 1815–1824 (2018)
19. Jun, C.S., Kwon, B.I.: Performance comparison of a spoke-type PM motor with different permanent magnet shapes and the same magnet volume. IET Electr. Power Appl. **11**(7), 1196–1204 (2017)