Speed Regulation Method Using Genetic Algorithm for Dual Three-phase Permanent Magnet Synchronous Motors

Xiuhong Jiang, Yuying Wang, and Jiarui Dong

***Abstract*—Dual three-phase Permanent Magnet Synchronous Motor (DTP-PMSM) is a nonlinear, strongly coupled, high-order multivariable system. In today's application scenarios, it is difficult for traditional PI controllers to meet the requirements of fast response, high accuracy and good robustness. In order to improve the performance of DTP-PMSM speed regulation system, a control strategy of PI controller based on genetic algorithm is proposed. Firstly, the basic mathematical model of DTP-PMSM is established, and the PI parameters of DTP-PMSM speed regulation system are optimized by genetic algorithm, and the modeling and simulation experiments of DTP-PMSM control system are carried out by MATLAB/SIMULINK. The simulation results show that, compared with the traditional PI control, the proposed algorithm significantly improves the performance of the control system, and the speed output overshoot of the GA-PI speed control system is smaller. The anti-interference ability is stronger, and the torque and double three-phase current output fluctuations are smaller.**

***Index Terms*—Dual three-phase permanent magnet synchronous motor, Genetic algorithm, PI control, Speed regulation.**

I. Introduction

PERMANENT magnet synchronous motor (PMSM) has advantages like high power and high efficiency. With the rapid development of the AC speed regulation technology, its application is becoming more and more extensive, and it is favored in high-reliability applications such as aerospace, national defense, and electric vehicle drives, especially since multi-phase PMSM came into public view. Multi-phase PMSM has obvious advantages over conventional three-phase PMSM in high stability, and it has small rotor harmonic loss and small torque ripple, etc. It has good fault-tolerant performance under the open-circuit fault of the stator, and it can still work in the absence of phase [1]-[2]. Nevertheless, the multi-phase PMSM will still be affected by many external disturbances and internal perturbations in actual operation. Consequently, the control requirement for multi-phase PMSM increases.

In recent years, there has been a lot of research on three-phase motor speed regulation strategies. For example, PI control is a commonly used strategy for traditional three-phase PMSM speed regulation systems [3]. However, traditional PI control does not have global optimization capabilities, and the PI parameter tuning process is very cumbersome. It is generally required to utilize the empirical trial and the error method to determine PI parameters, which leads to large fluctuations in the motor speed and torque, and cannot meet the requirements of the high-precision servo speed regulation system. A series of intelligent control strategies have also been proposed by some scholars, such as the use of fuzzy control [4]-[5], neural network [6] and other algorithms combined with traditional PI controller to realize the speed regulation of three-phase PMSM. However, fuzzy control has strict requirements for the selection of fuzzy rules and proportional parameters. The above-mentioned research algorithms are basically applied only to three-phase motors. At present, there is little research on the speed regulation of multi-phase motors. Taking dual three-phase permanent magnet synchronous motor (DTP-PMSM) as an example, which is a popular multi-phase motor. More research on DTP-PMSM focuses on motor simulation modeling and phase-deficient fault-tolerant control [7]-[12]. Literature [7]-[9] established the control model of DTP-PMSM, and realized the speed regulation of vector control algorithm. However, parameter optimization has not been researched. Literature [13] carried out proportional resonance control for the DTP-PMSM speed regulation system, but it cannot control multiple PI parameters well.

On the basis of establishing the simulation model of DTP-PMSM speed regulation system, this paper combines genetic algorithm (GA) [14]-[17] with PI controller to design a GA-PI speed controller to adjust and optimize 10 parameters globally in real time, it improves the control accuracy and robustness of DTP-PMSM speed regulation system. The simulation results prove that the GA-PI speed controller [18]-[20] has better stability and anti-interference ability under

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the conditions of specified speed and load disturbance, and the GA-PI speed controller can effectively suppress the effect of parameter perturbation.

II. Mathematical Modeling of DTP-PMSM

Fig. 1 shows the principle of DTP-PMSM driver. The spatial displacement of DTP-PMSM in this paper between two three-phase windings (ABC and UVW) is 30°[21].

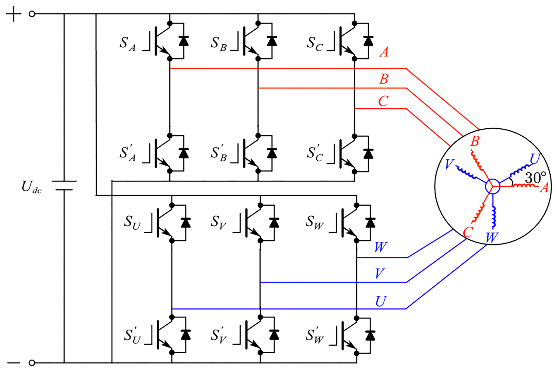


Fig. 1. Schematic of DTP-PMSM driver.

At present, there are two commonly used multi-phase PMSM modeling methods [22]: one is the *n-dq* modeling method: For an $n*m$-phase PMSM, the m-phase symmetric winding is regarded as a basic unit, and modeling it in the same way as m-phase winding. The other is the vector space decoupling (VSD) method, which regards the n-phase motor as a whole, and obtains the mathematical model of the rotating coordinate system through $C_{6s/2s}$ and $C_{2s/2r}$ coordinate transformation matrices, respectively. The various variables in the motor are divided into the $d-q$ -plane that participates in the electromechanical energy conversion and other planes that are not related to the energy conversion. Finally, the voltage equation, electromagnetic torque equation and motion equation are constructed under vector space decoupling.

This paper adopts the vector space decoupling method, which can theoretically solve the static and dynamic performance problems of AC speed regulation system, and has excellent dynamic performance and is more general. When the VSD modeling method is applied, the flux linkage phenomenon existing between the two sets of winding in the dual $d-q$ modeling method can be eliminated, it makes the mathematical model of DTP-PMSM simpler. In order to facilitate the modeling of DTP-PMSM, the following assumptions are needed [23]-[24]:

1) The influence of high-order space harmonic magnetomotive force is neglected, the air-gap magnetic field generated by the stator current and rotor permanent magnet is distributed according to the sinusoidal distribution.

2) Magnetic saturation of the motor core is neglected.

3) The mutual leakage inductance between the winding is neglected (the mutual inductance coefficient corresponding to the leakage flux).

4) Damp windings have already been transformed to equivalently two-phase orthogonal windings, which are located in axis respectively.

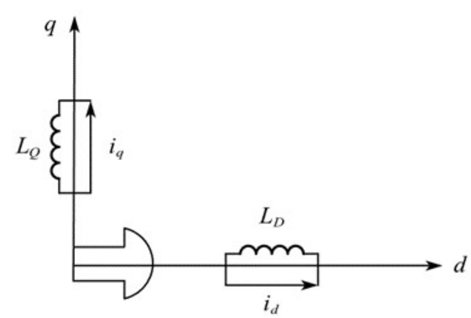
Through the vector space decoupling matrix, each variable of DTP-PMSM is mapped to three mutually orthogonal subspaces, namely α-β subspace, x-y subspace and zero-sequence subspace, in which zero-sequence subspace does not participate in energy conversion. Through the static space vector decoupling matrix, the transformation of DTP-PMSM from the natural coordinate system to the static coordinate system α-β can be completed. The transformation matrix $T_{\alpha\beta}$ is as follows:

$$T_{\alpha\beta}=\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & -\frac{1}{2} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \tag{1}$$

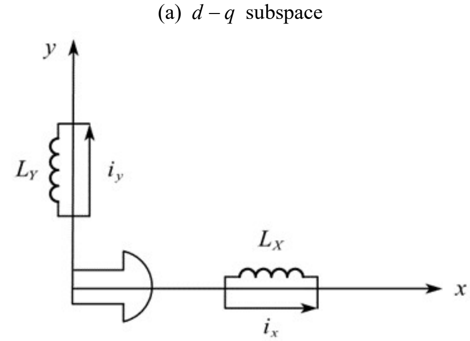
Similarly, the transformation matrix T_{dq} for transforming the stationary coordinate system $\alpha-\beta$ to the synchronous rotating coordinate system $d-q$ is

$$T_{dq}=\begin{matrix} d \\ q \\ x \\ y \\ o1 \\ o2 \end{matrix}\begin{bmatrix} \cos\theta_e & \sin\theta_e & & & & \\ -\sin\theta_e & \cos\theta_e & & & & \\ & & 1 & & & \\ & & & 1 & & \\ & & & & 1 & \\ & & & & & 1 \end{bmatrix} \tag{2}$$

The mathematical model of DTP-PMSM vector space decoupling is shown in Fig. 2.



(a) $d-q$ subspace



(b) $x-y$ subspace

Fig. 2. Vector space decoupling mathematical model of DTP-PMSM.

From the above VSD transformation, the voltage and current equations in the $d-q$ rotating coordinate system and the $x-y$ subspace are obtained as follows:

$$\begin{cases} u_d = Ri_d + L_d \dfrac{di_d}{dt} - L_q i_q \omega_e \\ u_q = Ri_q + L_q \dfrac{di_q}{dt} - L_d i_d \omega_e + \psi_f \omega_e \end{cases} \quad (3)$$

$$\begin{cases} u_x = Ri_x + L_z \dfrac{di_x}{dt} \\ u_y = Ri_y + L_z \dfrac{di_y}{dt} \end{cases} \quad (4)$$

In the above formula, u_d , u_q are the voltages of stator in the d and q axis respectively; i_d , i_q are the currents of stator in the d and q axis respectively; L_d , L_q are the inductances of stator in the d and q axis respectively; ω_e is the rotor electrical angular velocity; R is the stator resistance ; ψ_f is the permanent magnet flux linkage; u_x , u_y are the voltage components in the $x-y$ subspace respectively; i_x , i_y are the stator current in the $x-y$ subspace respectively; L_z is the leakage self-inductance.

The torque equation of DTP-PMSM is

$$T_e = \frac{P_n}{2} i_q [i_d (i_d - i_q) + \psi_f] \quad (5)$$

In the formula, P_n represents the pole pair number of the motor.

The mechanical motion equation of DTP-PMSM is

$$J \frac{d\omega_m}{dt} + B\omega_m + T_L = T_e \quad (6)$$

ω_m is the mechanical speed of the motor, T_L is the load torque, J is the rotational inertia, and B is the viscous friction coefficient.

III. GA-PI Speed Regulation Module of DTP-PMSM

GA is a parallel random search optimal method derived from Holland's biological evolutionary law of simulating the "survival of the fittest and survival of the fittest" in nature. As a randomized search algorithm, the variables of the initial solution are first operated on by "copying", "crossing", and "mutating" by generating an initial set of solutions. Through individual fitness indicators, individuals with low fitness are eliminated, so that the entire "population" develops in a more suitable direction to the environment, so as to obtain the optimal solution. Theoretically, under the premise of retaining the best individuals of the previous generation, the genetic algorithm is globally converged during the iteration process and has strong global search ability. Therefore, this paper combines GA with traditional PI control to design a speed regulator for permanent magnet synchronous motor system that can use genetic algorithms to automatically adjust parameters, and its structure diagram is shown in Fig. 3.

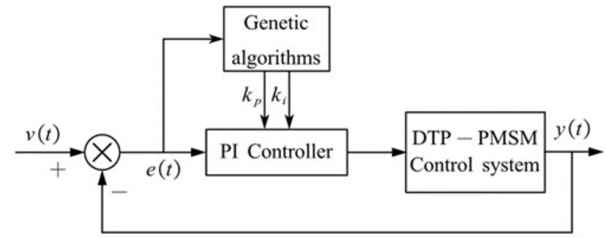


Fig. 3. Design principle of GA-PI speed regulation module.

The genetic algorithm is used to perform the optimization problem of PI parameters in the PI speed controller, and the deviation value $e(t)$ between the set value $v(t)$ and the feedback $y(t)$ is entered into the genetic algorithm module. k_p and k_i of the PI controller in the speed loop and the current loop are obtained by offline iterative calculation of the genetic algorithm. The simulation of GA-PI speed regulation system under SIMULINK is shown in Fig. 4.

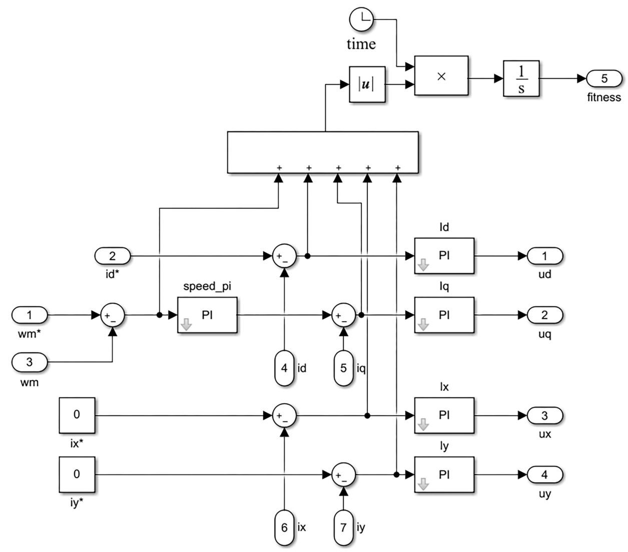


Fig. 4. Simulation of GA-PI speed regulation system.

GA-PI speed regulation system uses the m function to write the genetic algorithm, defines the 10 variable parameters of the PI controller, and the algorithm corresponds to the parameters of the PI control module in Simulink, and defines the parameters of the genetic algorithm, the upper and lower limits of the target parameters, and the fitness function. Then, the call statement is used in the program to drive the Simulink model to run, and the m function is interconnected with the PI control module in the Simulink simulation. After that, initialization begins, entering the loop (calculating objective function values, calculating fitness, selection, crossover, variation), reaching the number of iterations, the optimal value reached during the output loop.

The GA-PI speed regulation system includes a speed PI controller and 4 current PI controllers. Since the traditional vector control system does not consider the influence of the $x-y$ subspace, the current harmonic content is relatively large, so on the basis of using two current controllers in the traditional $d-q$ subspace, the current controller in the $x-y$ subspace is added. Among them, the parameters of the speed PI controller are $k_{p\omega}$, $k_{i\omega}$; the parameters of the d-axis current PI controller are k_{pd}, k_{id}; the parameters of the q-axis current PI controller are k_{pq}, k_{iq}. The parameters of the x-axis current PI controller are k_{px} and k_{ix}; the parameters of the y-axis current PI controller are k_{py} and k_{iy}. During each sampling process, the GA-PI speed controller will adjust the PI parameters once until it reaches a steady state or reaches the set iteration value. The operation steps of the GA-PI speed regulation system are as follows.

Step 1. Establish an initial population, namely the set of the above 10 PI controller parameter solutions, and set the parameters of the genetic algorithm. The population size value N and the genetic iteration value Gen are set to 50 and 100, respectively. The crossover probability value is set to 0.8 and the mutation probability value is set to 0.001.

Step 2. Calculate the fitness of individuals in the initial population according to the expected value.

Step 3. The specific operation of genetic algorithm is used to optimize the PI parameters. The GA method has three main operators that are selection, crossover and mutation.

1) Selection. Taking fitness as the selection principle, select individuals with higher fitness from the parent population to optimize the population.

2) Crossover. For the individuals selected for breeding the next generation, randomly select the same position of the two individuals, and execute the exchange at the selected position according to the crossover probability.

3) Mutation. According to the principle of genetic mutation, mutation is executed on some bits of some individuals with mutation probability.

Step 4. When the number of loops reaches the set algebra value of 100, the conditions for stopping evolution are satisfied, the iterative process of the algorithm converges, and the algorithm ends. Otherwise, replace the previous generation population with the new generation population obtained by selection, crossover, and mutation, and return to step 2 to continue the loop execution.

IV. Simulation Modeling of DTP-PMSM Speed Regulation System

A. *Speed Regulation System of DTP-PMSM*

The principle of the VSD control system for DTP-PMSM is shown in Fig. 5, which mainly consists of speed GA-PI controller, current GA-PI controller, coordinate transformation module and SPWM module, etc.

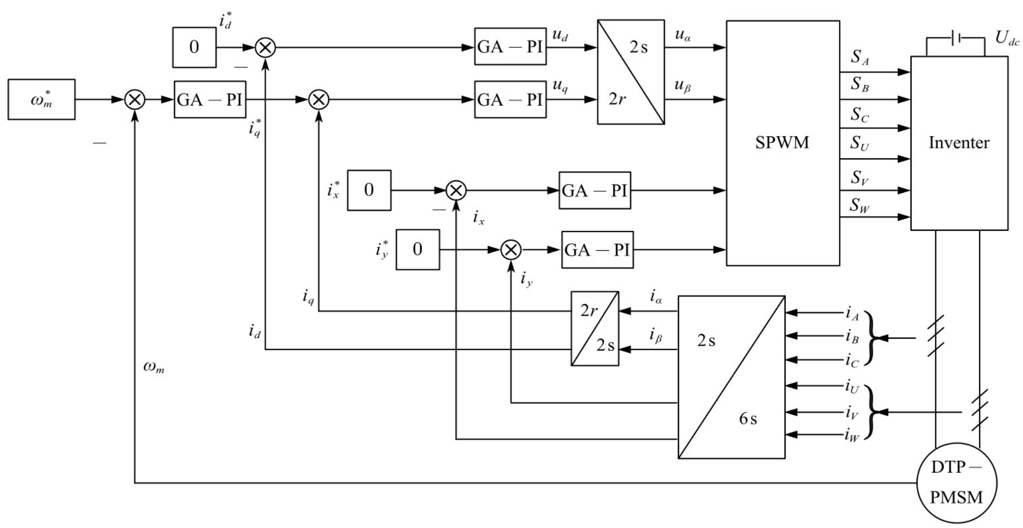


Fig. 5. The schematic diagram of the VSD control system of DTP-PMSM.

The rated speed ω_m^* has been given in this system, which is minus the actual speed ω_m generated by the DTP-PMSM, and then obtains the torque current reference value i_q^* through the speed PI controller. At the same time, the direct axis reference current $i_d^* = 0$ has been given. In order to ensure that the motor has the smallest stator copper loss when outputting the same electromagnetic torque, the rated values i_x^* and i_y^* of the $x-y$ -axis current are both set to zero, the current rating is set to be different from the current value fed back by the motor, and the current is input. The parameters are adjusted by the loop controller, so that the system has better start-up characteristics and dynamic stability. After adjustment, the direct-axis and quadrature-axis components u_d and u_q are output, and then the voltage reference value in the static coordinate system is obtained by $C_{2r/2s}$ transformation. The SPWM algorithm module is input to generate a PWM signal, and 12 PWM pulse sequences are used to control 12 IGBT to turn on or off respectively, the AC signal can be obtained on the dual three-phase stator windings, thereby driving the DTP-PMSM to operate.

B. *Simulation of DTP-PMSM Speed Regulation System*

The simulation platform of DTP-PMSM speed regulation system is established by MATLAB/SIMULINK. Its packaging and interface design are carried out. The various modules of the simulation model are shown in Fig. 6.

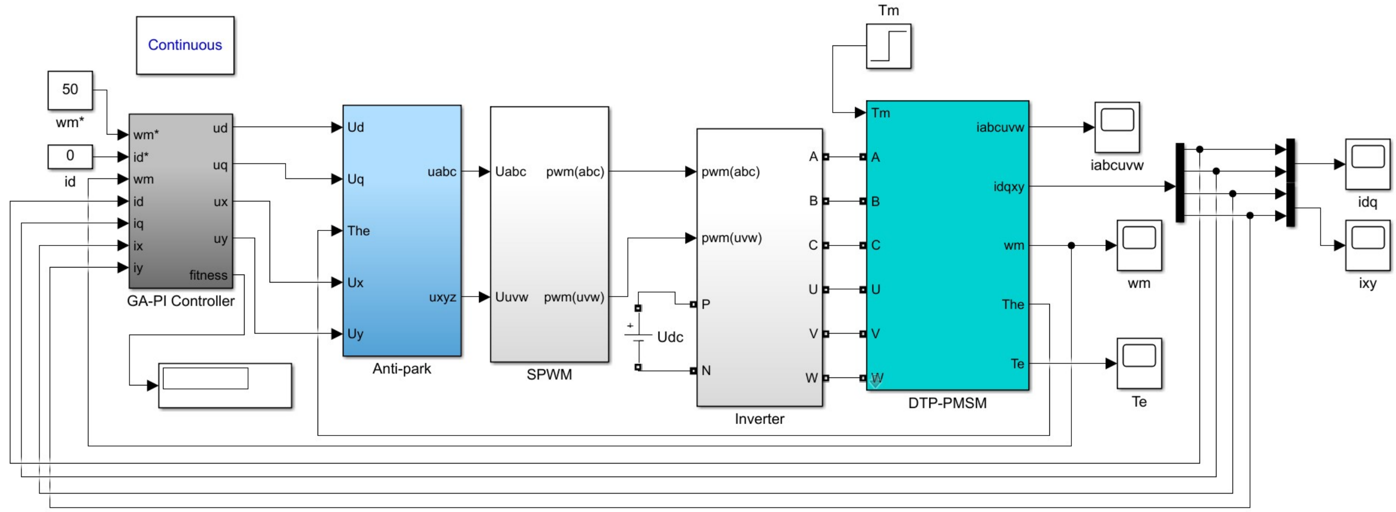


Fig. 6. Simulation of DTP-PMSM speed regulation system.

The simulation system consists of DTP-PMSM, GA-PI control module, anti-park coordinate transformation module, SPWM algorithm module, etc. The simulation of vector control and speed regulation of DTP-PMSM is realized through closed-loop control. The GA-PI control module optimizes the regulation of the motor speed and current. The anti-park coordinate transformation module converts $d-q$ coordinate to ABC, UVW coordinate. The SPWM algorithm module generates two PWM waves by comparing the triangular carrier wave with the symmetrical dual-phase sine modulation wave. The inverter module is mainly composed of switching elements such as transistors. By regularly turning the switching elements on and off repeatedly, the effect of direct current on alternating current output is achieved. The DTP-PMSM is the principal part of the entire simulation system. The output voltage by the inverter module drives the DTP-PMSM to produce signals such as current, speed, torque, and sets the rated torque T_m at the particular time.

V. Comparison of Simulation Results

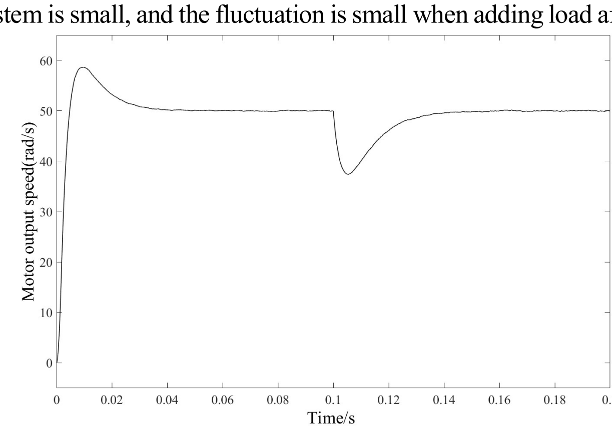
Assign values to the following parameters of the DTP-PMSM speed regulation system. Pole pairs $P_n = 3$, stator inductance $L_d = 8.8\text{mH}$, $L_q = 8.8\text{mH}$, stator resistance $R = 1.4\Omega$, flux linkage $\psi_f = 0.68\text{Wb}$, moment of inertia $J = 0.015\text{kg}\cdot\text{m}^2$, damping coefficient $B = 0\text{N}\cdot\text{m}\cdot\text{s}$, DC side voltage $U_{dc} = 311\text{V}$, the reference mechanical angular velocity $\omega_m^* = 50\text{rad/s}$, sampling period $T_s = 5e-05\mu\text{s}$. The variable step size ode23tb algorithm is applied and the simulation time is 0.2s. In addition, the load torque is $0\text{N}\cdot\text{m}$ at the beginning, when 0.1s, the load torque goes up to $100\text{N}\cdot\text{m}$.

The simulation adopts the closed loop control mode, and the controllers of the speed loop and the current loop are optimized and adjusted by the genetic algorithm. After genetic algorithm iteration, the optimal matching initial parameters of the PI regulator are obtained. The parameters of the speed loop PI controller $k_{p\omega} = 2.3514$, $k_{i\omega} = 88.7201$; the parameters of the d-axis current loop PI controller $k_{pd} = 8.4384$, $k_{id} = 714.5551$; the parameters of the q-axis current loop PI controller $k_{pq} = 9.6899$, $k_{iq} = 25.6729$; the x-axis current loop PI controller parameter $k_{px} = 3.0291$, $k_{ix} = 767.194$; the y-axis current loop PI controller parameter $k_{py} = 2.7135$, $k_{iy} = 89.1529$.

The parameters of the traditional PI regulator are set as follows for comparison. The parameter of the speed loop PI controller $k_{p\omega} = 1$, $k_{i\omega} = 80$; the parameter of the d-axis current loop PI controller $k_{pd} = L_d \times 1200$, $k_{id} = R \times 1200$; the parameter of the q-axis current loop PI controller $k_{pq} = L_q \times 1200$, $k_{iq} = R \times 1200$. The parameters of the x-axis and y-axis current loop PI controller $k_{px,y} = L_z \times 1200$, $k_{ix,y} = R \times 1200$.

Substitute the PI controller parameters obtained by the genetic algorithm operation into the DTP-PMSM model. The results obtained after the simulation are shown in Fig. 7-9.

According to the output waveform, the speed, torque and three-phase current of the traditional PI control system fluctuate greatly in the motor startup stage, and the speed stabilized after 0.04 s. However, the overshoot of the GA-PI speed regulation system is small, and the fluctuation is small when adding load after



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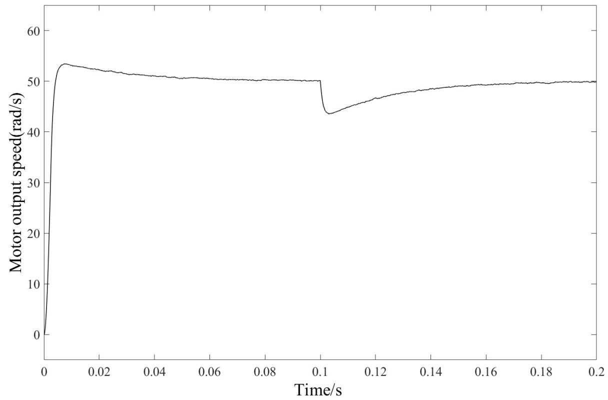
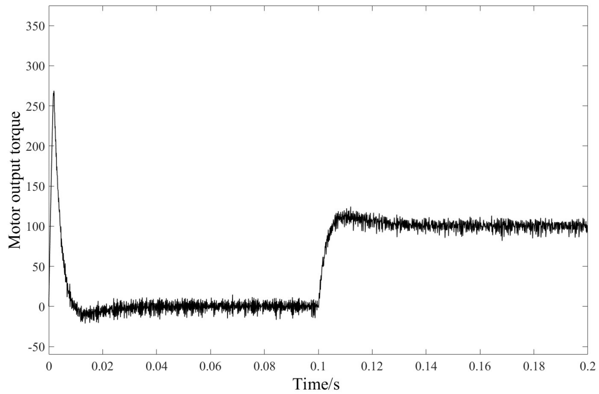


(b)

Fig. 7. Comparison of motor speed. (a) Rotation speed of DTP-PMSM vector control method based on traditional PI control. (b) Rotation speed of DTP-PMSM vector control method based on GA-PI control.



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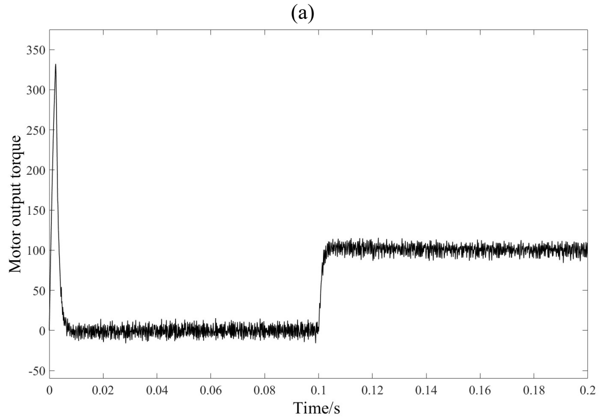
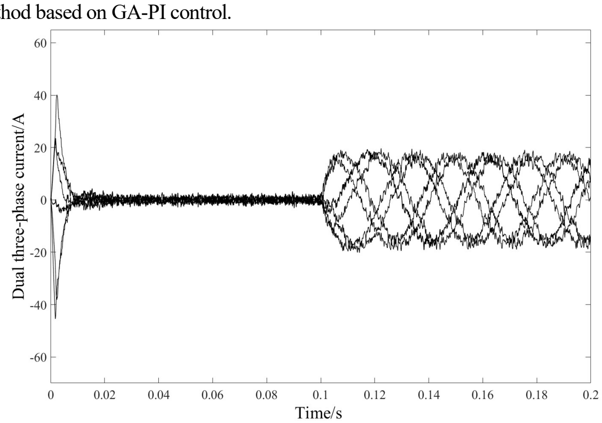


(b)

Fig. 8. Comparison of motor torque.(a) Torque of DTP-PMSM vector control method based on traditional PI control.(b) Torque of DTP-PMSM vector control method based on GA-PI control.



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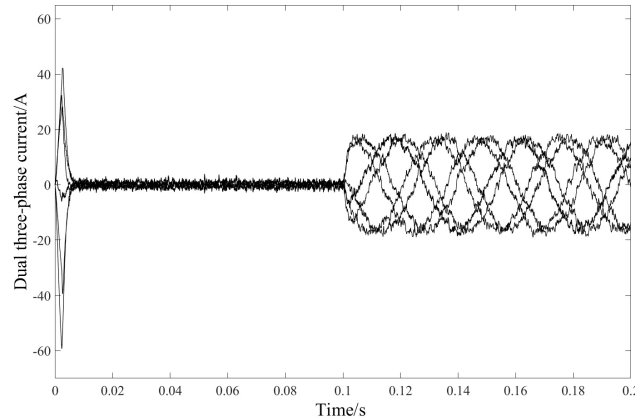
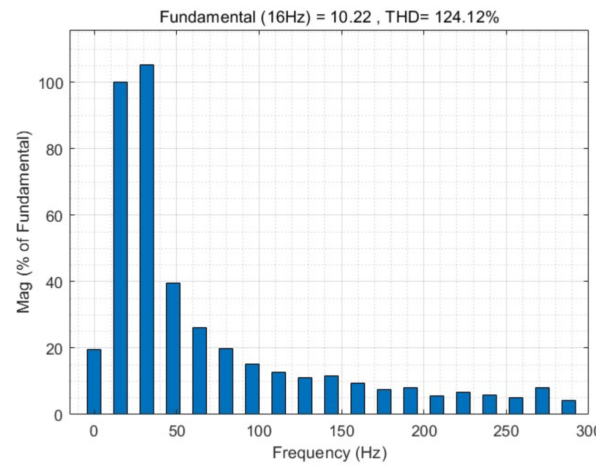


(b)

Fig. 9. Comparison of dual three-phase current.(a) Dual three-phase current of DTP-PMSM vector control method based on traditional PI control.(b) Dual three-phase current of DTP-PMSM vector control method based on GA-PI control.



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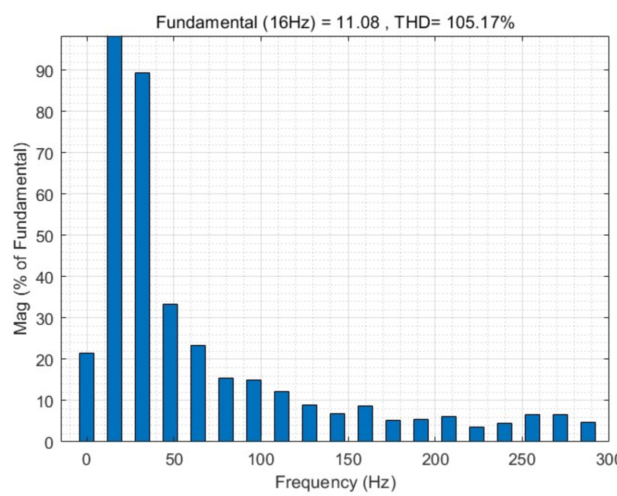

(b)

Fig. 10. FFT results of the phase currents after 0.12s. (a) FFT results of the phase currents after 0.12s of DTP-PMSM vector control method based on traditional PI control.(b) FFT results of the phase currents after 0.12s of DTP-PMSM vector control method based on GA-PI control.

0.1s. As shown in Fig. 10 is the FFT result of one phase current in the six-phase current after 0.12s, it can be seen that the value of total harmonic distortion (THD) is reduced by 18.95%. In contrast, the degree of phase current distortion after GA-PI treatment is reduced. Compared with the traditional PI control system, the speed output overshoot of the GA-PI speed control system is smaller and the anti-interference ability is stronger.

VI. Conclusion

In this paper, the improved DTP-PMSM control system based on PI and genetic algorithm is proposed. According to the mathematical model of DTP-PMSM, the GA-PI speed controller is used to effectively control the motor speed, and the algorithm simulation is carried out through SIMULINK. The simulation results prove that the GA-PI speed regulation system is more stable in the control of the permanent magnet synchronous motor, and the algorithm optimization performance is better, so that the system has better starting characteristics and anti-interference characteristics. Compared with the conventional PI control method, the DTP-PMSM vector control PI closed-loop speed regulation method based on genetic algorithm can process multiple PI parameters at the same time, and it has better anti-disturbance, which verifies its effectiveness and feasibility.

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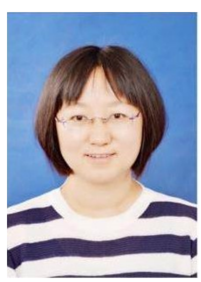

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