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Research on Efficiency Optimization Based on Permanent Magnet Synchronous Linear Motor

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Abstract—In recent years, permanent magnet synchronous linear motor (PMSLM) has gained tremendous momentum in industry, especially in the high-precision field. This is mainly because it has the advantages of small size, high control precision, and reliable operation. However, due to the special structure of linear motor, the control strategy of rotating motor cannot be directly applied to PMSLM. Three control strategies for reducing loss and improving efficiency of PMSLM are proposed in this paper. Firstly, the mathematical model of PMSLM is established, and the loss model and efficiency equation are established. Secondly, we adopt the loss model control strategies of $i_d = 0$, and maximum thrust current ratio and direct thrust are used to optimize the efficiency of the motor. Finally, simulation experiments are carried out for the three proposed optimization strategies, and the effects of initial speed and load on motor efficiency are analyzed. The effectiveness of the three loss model control strategies proposed in this paper is fully verified by the simulation results, and it is found that the loss model control strategy of $i_d = 0$ has the most obvious efficiency improvement.

1. INTRODUCTION

PMSLM is widely used in various scenarios because of its simple structure, high thrust density, high control accuracy, low mechanical loss, and fast dynamic response [1]. The "14th Five-Year Plan" outline puts forward the goal of "striving to achieve carbon peaks by 2030 and carbon neutrality by 2060" [2]. Our country is accelerating the transformation of the energy industry and building a low-carbon, green, safe and efficient energy system. In recent years, China has continuously emphasized "carbon neutrality" and "carbon peaking" [3]. The rational distribution of energy and reduction of energy consumption are particularly important. This article mainly focuses on the efficiency optimization research of PMSLM, in order to reduce the waste of energy in the operation of the motor.

At present, the optimization control technology for motor efficiency is mainly divided into two categories. One is the model method. The model method obtains a relatively complete motor loss model through the analysis of the internal parameters of the motor, and by solving the loss equation, the current, voltage, flux linkage, etc. Then, the maximum efficiency of motor operation can be obtained by using the optimization mathematical method. The other is the search method, which continuously changes the current, voltage, fluxs, etc. through the iterative algorithm to monitor the motor efficiency in real time so as to obtain the maximum efficiency of the motor operation [4–6]. The accuracy of the model method depends on the accuracy of the motor model, and it is very dependent on the parameters of the motor itself. If the parameters of the motor change, then the calculation results will have a big deviation from the actual situation. The search method is not affected by motor parameters, but is mainly affected by iterative algorithm and iterative convergence requirements. The search method is complex; the calculation time is long; and the hardware requirement is relatively high.

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The model method is relatively simple; the calculation time is short; and the hardware requirement is low. Therefore, most of them use the model method to analyze the motor [7–9].

Based on the model method, this paper adopts the $i_d = 0$, maximum thrust current ratio, and direct thrust loss model control strategy to optimize the efficiency of PMSLM. The loss of the motor mainly includes copper loss, iron loss, stray loss, mechanical loss, etc. This paper mainly considers the two major losses, copper loss and iron loss, deduces the loss model and efficiency equation of the motor, and obtains the maximum operation efficiency of the motor. The simulation results show that the efficiency of the motor is improved by 16.42% through the $i_d = 0$ loss model control strategy.

2. EFFICIENCY MODEL OF PMSLM

2.1. Mathematical Model of PMSLM

In order to establish the mathematical model of PMSLM, it is necessary to idealize the assumption of PMSLM, which is as follows:

(i) It is assumed that the primary alveolar effect is ignored.
(ii) Ignore core saturation, eddy current, and hysteresis loss.
(iii) The primary upper undamped winding and permanent magnet have no damping effect.
(iv) The magnetic field produced by permanent magnet and the induced magnetic field produced by three-phase winding have sinusoidal distribution.

When the primary winding is connected to alternating current, a traveling wave magnetic field will be generated in the air gap. When the secondary permanent magnet is cut by the traveling wave magnetic field, it will produce induced electromotive force and current, which interact with the magnetic field in the air gap to produce electromagnetic thrust. The Structure schematic diagram of permanent magnet synchronous linear motor is shown in Fig. 1.

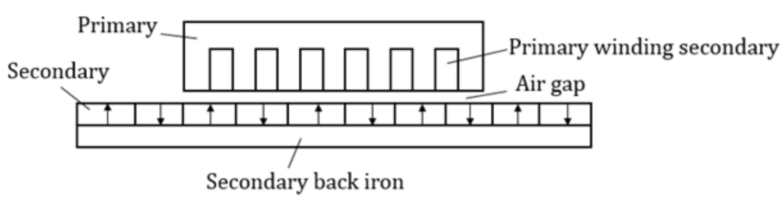

Figure 1. The Structure schematic diagram of permanent magnet synchronous linear motor.

In the d-q coordinate system, the mathematical model of PMSLM is as follows:

Voltage equation:

$$\begin{cases} U_d = Ri_d + p\psi_d - \omega\psi_q \\ U_q = Ri_q + p\psi_q + \omega\psi_d \end{cases} \tag{1}$$

where U_d and U_q are d-q axes voltages; R is the resistance of each phase primary winding; i_d and i_q are d-q axes primary currents; ψ_d and ψ_q are d-q axes fluxes; p is the differential operator; ω is the electrical angular velocity.

Flux linkage equation:

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{2}$$

where L_d and L_d are d-q axes inductance, and ψ_f is the permanent magnet flux.

Angular velocity and linear velocity relation equation:

$$\omega = \frac{\pi}{\tau} v \tag{3}$$

where τ is the motor pole pitch, and v is the synchronous linear speed of the motor.

2.2. Mathematical Model of PMSLM

Total output power:

$$P_{total} = \frac{3}{2}\left[R\left(i_d^2 + i_q^2\right) + \left(p\psi_d i_d + p\psi_q i_q\right) + \omega\left(\psi_d i_q - \psi_q i_d\right)\right] \tag{4}$$

where P_{total} is the total output power of the motor.

Loss equation:

$$P_{loss} = \frac{3}{2}\left[R\left(i_d^2 + i_q^2\right) + \left(p\psi_d i_d + p\psi_q i_q\right)\right] \tag{5}$$

where P_{loss} is the total output power of the motor.

Electromagnetic power equation:

$$P_e = \frac{3}{2}\omega\left(\psi_d i_q - \psi_q i_d\right) \tag{6}$$

where P_e is the electromagnetic power of motor.

Electromagnetic thrust equation:

$$F_e = \frac{P_e}{v} = \frac{3\pi}{2\tau}\left(\psi_d i_q - \psi_q i_d\right) \tag{7}$$

where F_e is the electromagnetic torque of motor.

Efficiency equation ignoring stray loss and mechanical loss of motor:

$$\eta = \frac{p_{total} - p_{loss}}{p_{total}} \times 100\% \tag{8}$$

where η is the efficiency of motor.

3. THREE EFFICIENCY OPTIMIZATION METHODS OF PMSLM

3.1. Model Control Strategy of $i_d = 0$

In motor control theory, the more commonly used vector control method is $i_d = 0$. If $i_d = 0$ can be guaranteed during the whole operation process of PMSLM, the electromagnetic thrust is only affected by the q axis component of stator current. The minimum value obtained by the extreme value method is i_d'. In this way, the copper loss produced during the operation of the motor can be greatly reduced, and the efficiency of the motor can be improved [10]. The schematic diagram of loss model control strategy of the $i_d = 0$ is shown in Fig. 2.

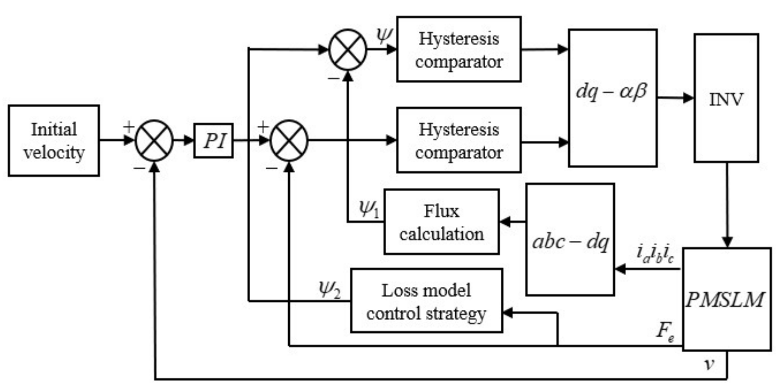

Figure 2. The loss model control strategy of $i_d = 0$.

According to formula (7).

$$i_q = \frac{2\tau F_e}{3\pi\left[\psi_f + \left(L_d - L_q\right) i_d\right]} \tag{9}$$

Equations (2) and (9) are brought into the form of Eq. (5)

$$\begin{aligned} P_{loss} \;=\; & \frac{3}{2}\left[R\left(i_d^2+\left(\frac{2\tau F_e}{3\pi\left[\psi_f+\left(L_d-L_q\right)i_d\right]}\right)^2\right)\right. \\ & \left.+\left(p\left(L_d i_d+\psi_f\right)i_d+pL_q\left(\frac{2\tau F_e}{3\pi\left[\psi_f+\left(L_d-L_q\right)i_d\right]}\right)^2\right)\right] \end{aligned} \tag{10}$$

When the system is in a stable state, the total loss is only related to i_d. Order $\frac{dP_{loss}}{di_d}=0$, the stator current d axis component of the minimum loss power can be obtained i_d'.

$$i_d' = \frac{\left[2\left(\frac{2\tau F_e}{3\pi}\right)^2\left\{\frac{R\left(L_d-L_q\right)+pL_q\left(L_d-L_q\right)}{\left[\psi_f+\left(L_d-L_q\right)i_d\right]}\right\}-p(2i_dL_d+\psi_f)\right]}{2R} \tag{11}$$

The simulation module of efficiency optimization is built according to Eqs. (9) and (11) as shown in Fig. 3.

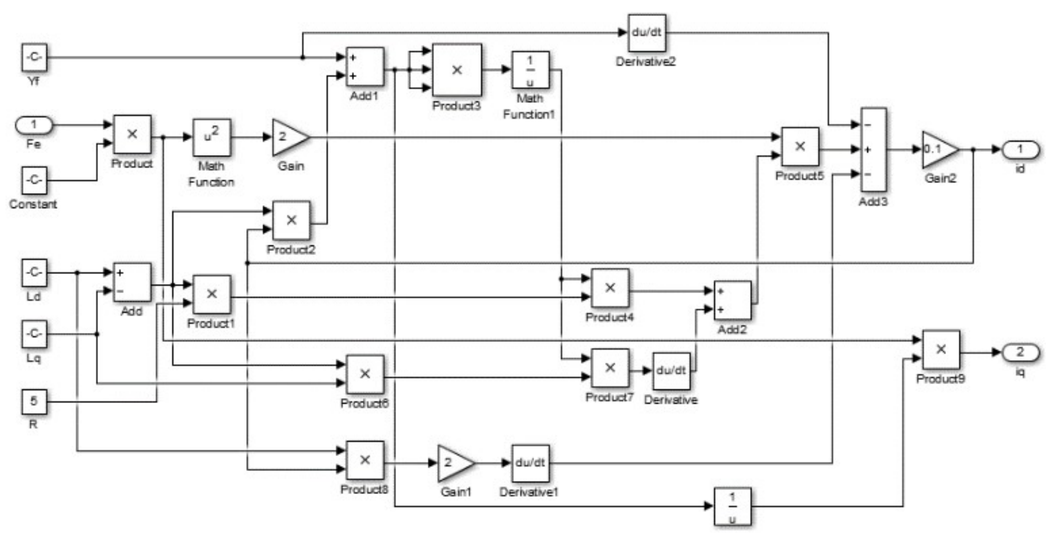

Figure 3. Simulation module of control strategy based on $i_d = 0$.

3.2. Loss Model Control Strategy of Maximum Thrust Current Ratio

When the loss model control strategy of maximum thrust current ratio is adopted, and the motor outputs the same electromagnetic torque, the current is minimum [11]. According to Eq. (5), the loss is closely related to the current. When the output power is constant, the smaller the current is, the smaller the loss is, and the higher the efficiency of the motor is. The schematic diagram of loss model control strategy for the maximum thrust current ratio is shown in Fig. 4.

Current equation:

$$i=\sqrt{i_d^2+i_q^2} \tag{12}$$

Under the constraint of torque condition, the minimum value of loss, i.e., the maximum of motor efficiency, can be obtained by finding the minimum value of Eq. (12). In the optimal problem, the Lagrangian multiplier method is a method to find the extreme value of a multivariate function whose variables are restricted by one or more conditions. According to the Lagrangian multiplier method, the auxiliary function is constructed as follows:

$$F=i_d^2+i_q^2+\lambda\left\{\frac{3\pi}{2\tau}\left[\psi_f i_q+\left(L_d-L_q\right)i_d i_q\right]-F_e\right\} \tag{13}$$

$$\begin{cases} \dfrac{\partial F}{\partial I_d} = 2i_d + \lambda \dfrac{3\pi}{2\tau} \left(L_d - L_q \right) i_q = 0 \\ \dfrac{\partial F}{\partial I_q} = 2i_q + \lambda \dfrac{3\pi}{2\tau} \left[\psi_f + \left(L_d - L_q \right) i_d \right] = 0 \\ \dfrac{\partial F}{\partial \lambda} = \dfrac{3\pi}{2\tau} \left[\psi_f i_q + \left(L_d - L_q \right) i_d i_q \right] - F_e = 0 \end{cases} \tag{14}$$

$$\begin{cases} i_d = \dfrac{3\pi \left(L_d - L_q \right) i_q^3}{2\tau F_e} \\ F_e = \dfrac{3\pi}{2\tau} \psi_f i_q + \dfrac{9\pi^2}{4\tau^2} \left(L_d - L_q \right)^2 \dfrac{i_q^4}{F_e} \end{cases} \tag{15}$$

where λ is the Lagrange operator. The simulation module of efficiency optimization is built according to formula (15) to build a simulation module optimized for efficiency as shown in Fig. 5.

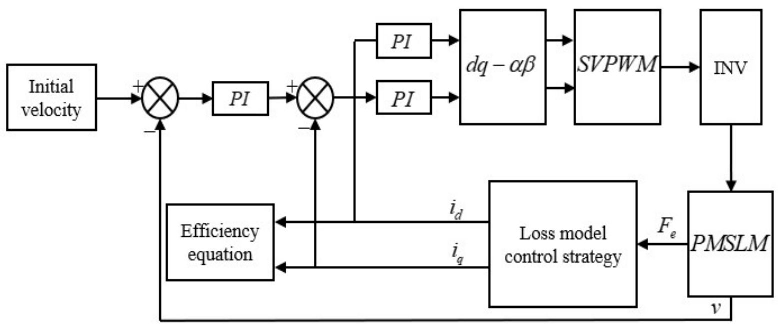

Figure 4. The loss model control strategy of maximum thrust current ratio.

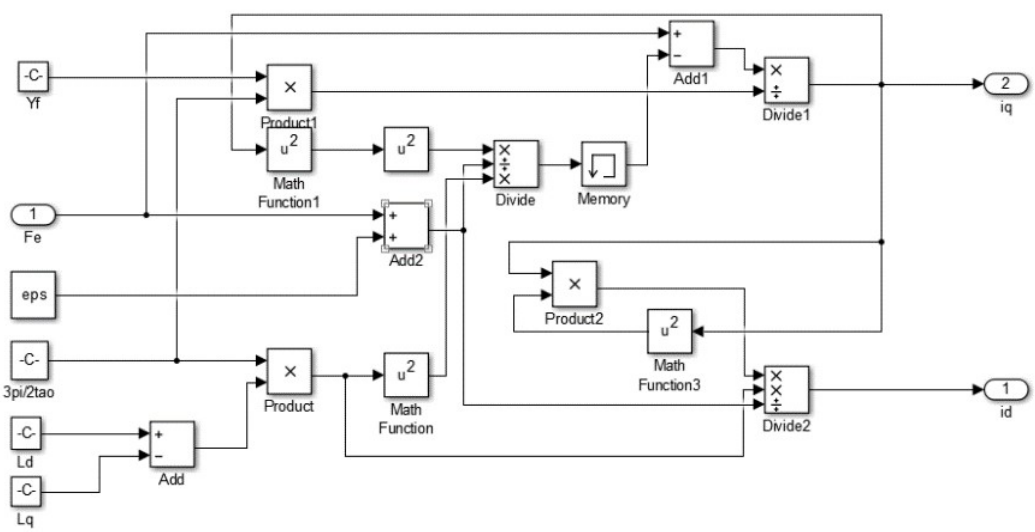

Figure 5. Simulation module of control strategy based on maximum thrust current ratio.

3.3. Loss Model Control Strategy of Direct Thrust

The direct thrust loss model control strategy takes the motor thrust as the control variable, which omits the intermediate control link and improves the dynamic response ability of the thrust. In dynamic control, because the control time is much less than the mechanical time constant of the rotor, it can be considered that the rotor flux vector remains constant in this short process, and as long as the amplitude of the stator flux vector is kept constant, the motor thrust can be controlled through the control angle [12–14]. The schematic diagram of loss model control strategy for the direct thrust is shown in Fig. 6.

The difference is made by using the flux obtained by the efficiency optimization and the flux obtained by the flux calculation module.

$$\begin{cases} \psi_1 = \sqrt{\psi_{d1}^2 + \psi_{q1}^2} \\ \psi_2 = \sqrt{\psi_{d2}^2 + \psi_{q2}^2} \\ \psi = \psi_2 - \psi_1 \end{cases} \tag{16}$$

The simulation module of efficiency optimization is built according to Equation (16) as shown in Fig. 7.

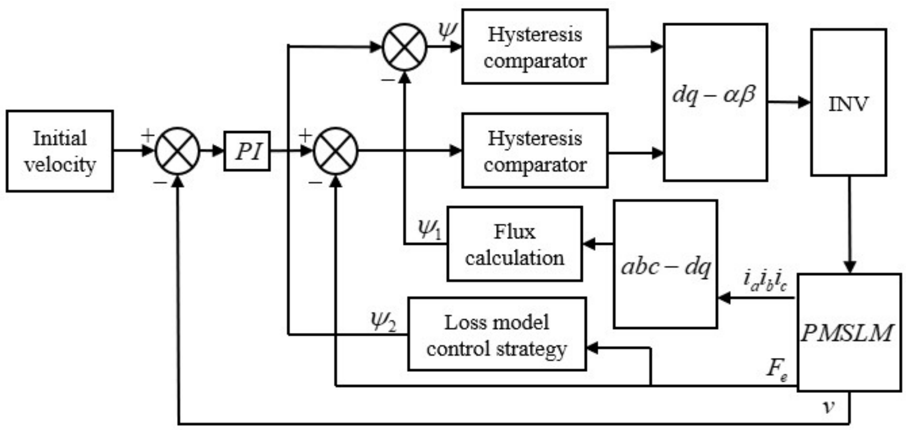

Figure 6. The loss model control strategy of direct thrust.

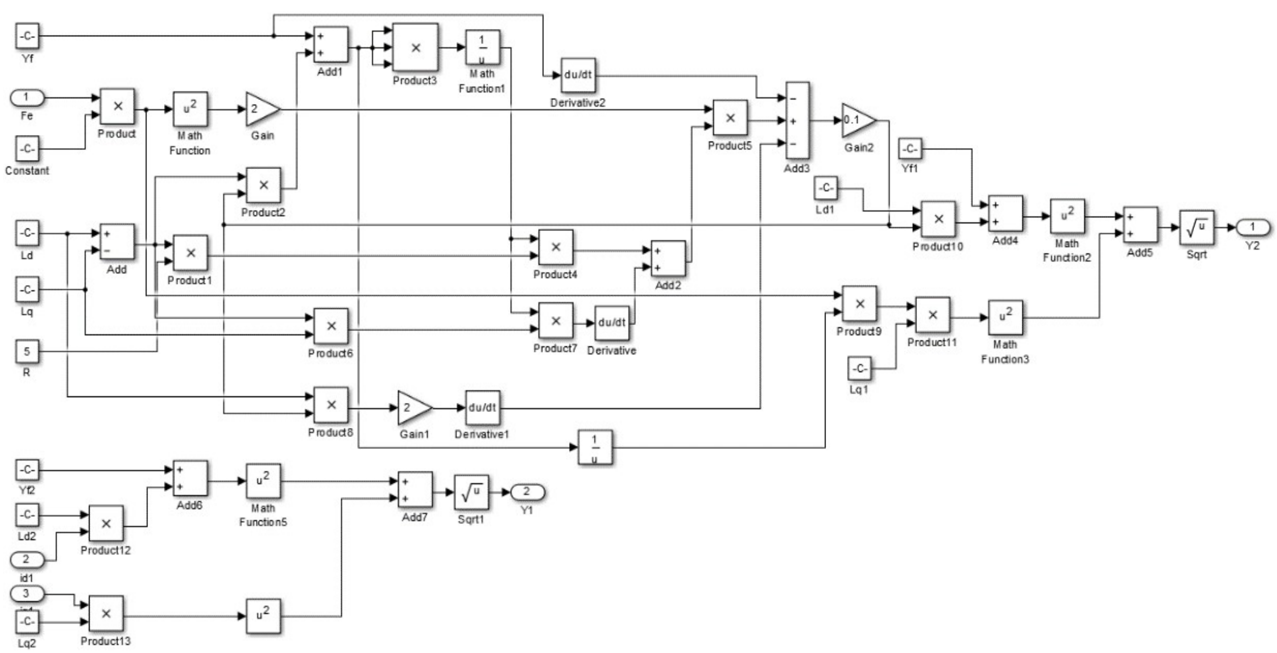

Figure 7. Simulation module of control strategy based on direct thrust.

4. SIMULATION RESULTS

In order to verify the three methods proposed in this paper, the motor model is established by SIMULINK, and simulation research is carried out. The loss model control strategy is called method 1 based on the loss model control strategy of the $i_d = 0$. The loss model control strategy of the maximum thrust current ratio is called the second method. The loss model control strategy of direct thrust is called the third method. Method 1, method 2, and method 3 are simulated under the condition that the initial speed is 0.2 m/s. The parameters of the motor are shown in Table 1. The result of the simulation is shown in Fig. 8.

Table 1. Motor parameters.

Simulation speed	n	0.2 m/s
D-axis inductors	L_d	0.02 H
Q-axis inductors	L_q	0.01 H
Permanent magnet chains	ϕ_f	0.05 Wb
Polar logarithm	p	1
Resistors	R	$5\,\Omega$
Viscous friction coefficient	B	$5\,\mathrm{N \cdot s/m}$
Pole distance	τ	0.01m
Rotor mass	M	1.5 kg
Rated speed	v	0.2 m/s
Rated load torque	F_L	$10\,\mathrm{N \cdot m}$

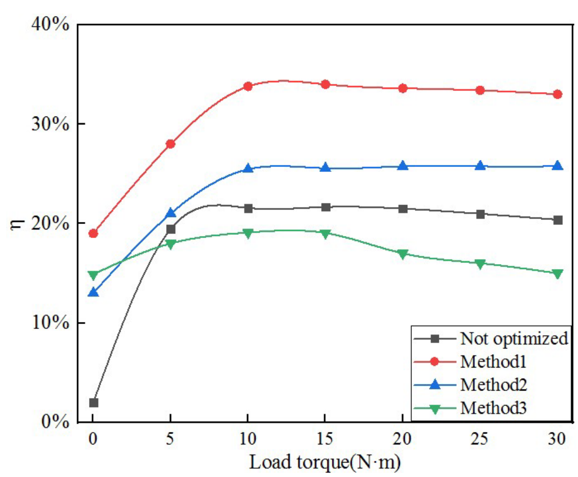

Figure 8. Comparison of operating efficiency of unoptimized, method 1, method 2 and method 3 under rated conditions.

As can be seen from Fig. 8, at the rated load torque of $10\,\mathrm{N \cdot m}$ and rated speed of 0.2 m/s, the operation efficiency of the not optimized motor is 21.56%; the efficiency optimized by method 1 is 33.8%; the efficiency optimized by method 2 is 25.46%; and the efficiency optimized by method 3 is 19.1%. It can be seen from the figure that the efficiency of the motor optimized by method 1 is the best. In the no-load state, the simulation time is 1 s, and the results of not optimized and method-1 optimized motor speed and electromagnetic thrust are shown in Fig. 9 and Fig. 10.

It can be seen from the figure that after method 1, the buffeting range of motor speed and

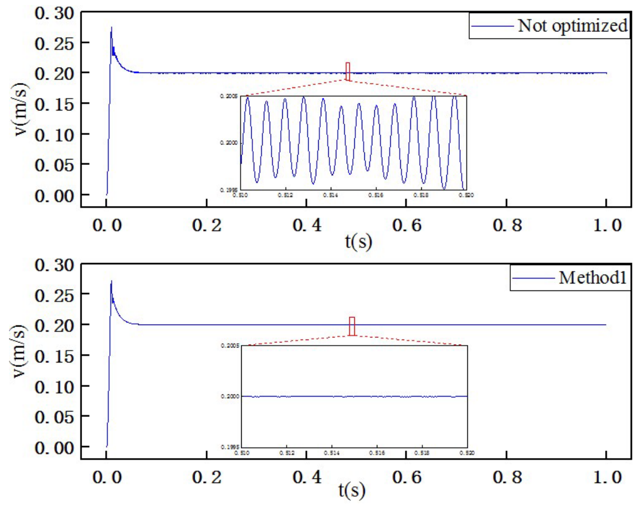

Figure 9. Speed comparison between not optimized and method 1.

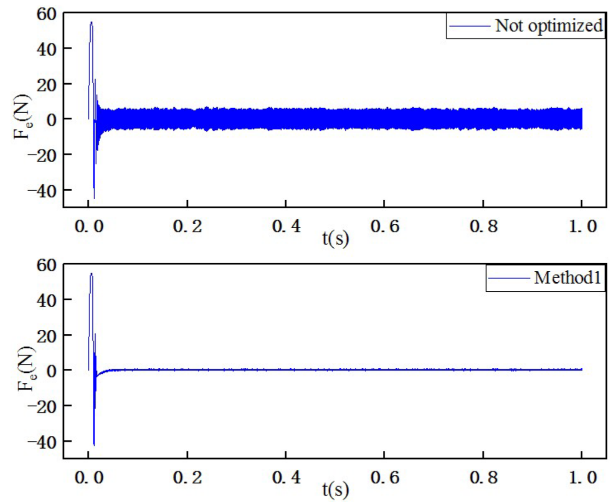

Figure 10. Electromagnetic push between out optimized and method 1.

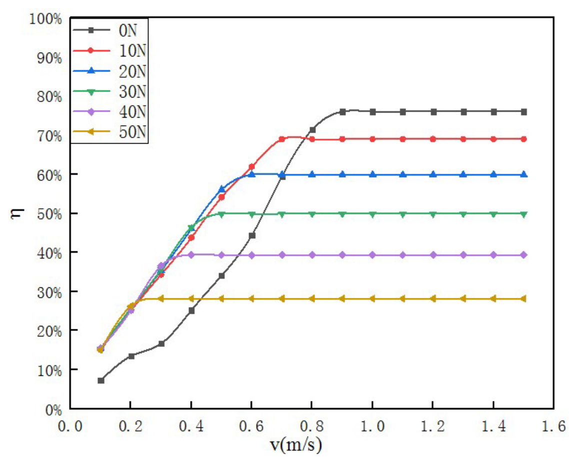

Figure 11. The influence of speed and load torque on motor efficiency.

electromagnetic thrust is obviously reduced, and the performance of each parameter is better than that before optimization.

As can be seen from Fig. 11, with the increase of a given speed, the efficiency of the motor increases, and after reaching a certain speed, the efficiency of the motor will not continue to increase with the increase of the given speed. The speed of this turning point decreases with the increase of motor load.

5. CONCLUSION

In this paper, firstly, by putting forward three methods to optimize the motor efficiency, the improvement of motor efficiency can be observed obviously. The loss model control strategy of $i_d = 0$ has the best effect, which increases the motor efficiency by 16.42% under no-load condition. Secondly, the influence of the initial speed and load of the motor on its operation efficiency is further analyzed. Under no load, the efficiency of the motor is the lowest, because all the output power becomes a loss output, and the efficiency of the motor increases rapidly with the increase of the load. After reaching the best state, as the load increases, the motor efficiency will decrease again. Finally, through the analysis of different speeds and loads, we can better grasp the law of motor operation efficiency and reduce the unnecessary waste of energy. In this paper, only the iron loss and copper loss of the motor are considered, and the influence of the edge effect of the linear motor on the efficiency should also be considered, so there is a deviation between the motor efficiency and the actual situation, and this method still has room for improvement. The loss model of the motor will continue to be improved, and the algorithm will be optimized.

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