Application and Control Method of Electromagnetic Synchronizer for Double Rotor Motor Power Coupling System

Jiang Kejun, He Ren, and Zhang Lanchun

Abstract—**On the double rotor motor power coupling system existing now, electromagnetic coupling of the inner motor is the only way to transmit engine power to drive axle. And this leads to the low transmission efficiency when the vehicle is driven by the engine. Aiming at this issue, this paper proposes the improvement measure, which is to add the electromagnetic synchronizer between the input shaft and the output shaft. According to the thinking of this measure, the paper analyzes the operating process of the electromagnetic synchronizer. Then using quadratic optimal control theory, the optimal PID control method is designed to control the duty ratio of the electromagnetic synchronizer driving voltage. In order to test the validity of the method, the paper builds the simulation model in Matlab/Simulink software. The simulation results indicate that the optimal PID control method can effectively control the work process of electromagnetic synchronizer. It can achieve the balance between frictional work and longitudinal jerk, and decrease the impact reasonably when the electromagnetic synchronizer switching its state.**

Index Terms—**Double rotor motor power coupling system, Electromagnetic synchronizer, Optimal control, Simulation and analysis**

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I. Introduction

DOUBLE rotor motor power coupling system was invited first by Martin Hoeijmaker in 2002[1], who was a professor at the Delft University of Technology. As a new-type power coupling system, it attracts more and more people's attentions now, and it has been considered as another new effective solutions for the hybrid electric vehicle[2-4]. Double rotor motor power coupling system is a non contact dynamic coupling system, and its structure and principle are shown in Fig.1[5-6]. This system mainly consists of the double rotor motor, the inverter/rectifier, the internal- combustion engine, the battery and the control unit. The double rotor motor can be divided again into the inner motor and the outer motor. The outer motor can drive the vehicle directly, and can change into a generator to convert the kinetic energy into electrical energy. Of course, the generator can provide the resisting moment to brake the vehicle. The inner motor can transmit engine power to drive axle by using the electromagnetic coupling effect. If necessary, it can change into the generator, and turn engine power into electricity.

According to the recent studies, this system has the advantages of simple structure, easy maintenance, no wear, and multiple operating modes[7-8].

According to the technical proposal of Professor Martin Hoeijmaker, the input shaft of the double rotor motor connects with the output shaft of the engine, and the output shaft connects with the drive axle. Electromagnetic coupling effect of the inner motor is the only way to transmit engine power to drive axle, and the electromagnetic torque of inner motor is the only load on the engine. This arrangement makes the engine working more freely, and can achieve the optimal control more easily.

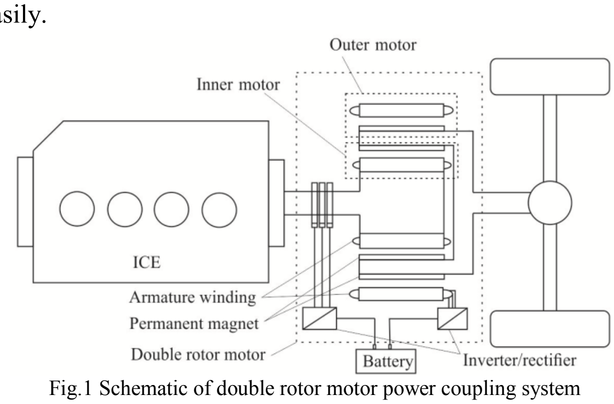

Fig.1 Schematic of double rotor motor power coupling system

Objectively speaking, the transmission efficiency of electromagnetic coupling is lower than mechanical transmission. This influences the comprehensive efficiency of the whole system. But if we use the electromagnetic synchronizer to connect the input shaft and the output shaft directly, as showed in Fig.2, we can overcome the shortcoming,

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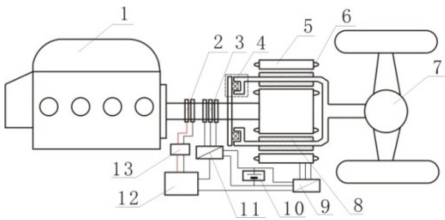
and realize the no-power-loss transmission. The result is improving the comprehensive fuel economy of the vehicle. On the same time, the mechanical joining can reduce the working temperature of the double rotor motor.

This article starts from the structure and principle of the electromagnetic synchronizer. Using the optimal control method to control the duty ratio of the electromagnetic synchronizer's driving voltage accurately. This paper will achieve good switch from electromagnetic drive to mechanical and direct transmission.



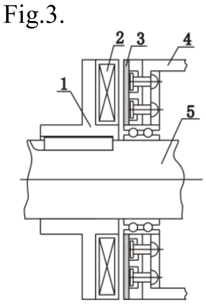
1-engine 2-power slip ring of electromagnetic synchronizer 3-power slip ring of inner rotor 4-electromagnetic synchronizer 5-stator coil 6-outer permanent magnet of outer rotor 7-drive axle 8- inner permanent magnet of outer rotor 9- inverter/ rectifier of outer motor 10-battery 11-inverter/ rectifier of inner motor 12-control unit 13-driving amplifier

Fig.2 Installation diagram of electromagnetic synchronizer

II. Principle and Operation Process of the Electromagnetic Synchronizer

A. Structure and Principle

The electromagnetic synchronizer makes the power transmission skip the double rotor motor, and it can transfer engine torque to the drive axle directly with the static friction effect. Similar to electromagnetic clutch[9], the electromagnetic synchronizer is consist of electromagnetic coil, active part, driven part, and armature iron, etc. The whole structure is shown in Fig.3.



1-active part 2-electromagnetic coil 3-armature iron
4-driven part (to the drive axle) 5-output shaft of engine
Fig.3 Structure diagram of electromagnetic synchronizer

According to the structure of the electromagnetic synchronizer, we can see the operation principle is as followed.

The electromagnetic coil produces the attractive force when energized, then the attractive force makes the armature iron move to the active part. The armature iron connects to the driven part by rivets, and the armature iron has a friction layer, which can rub on the active part when the armature iron touches the active part. The active part links to the output shaft of the engine by key joint. If the dynamic friction appears, the dynamic frictional force will be generated. And from this time, the active part turns the driven part by the dynamic frictional force. When the driven part turns as fast as the active part, the synchronizing process is achieved. Now the dynamic friction changes into static friction which becomes the main factor in transmission, and the power of the engine can be transferred to the drive axle by the static friction force.

B. Operation Process

According to the principle of electromagnetic synchronizer, the operation process of the electromagnetic synchronizer can be divided into four phases (as shown in Fig. 4). The first is gap-elimination phase (T1), in which the duty is to eliminate the gap between the electromagnetic coil and the armature iron, so general requirements of this phase are action rapidly and shortening time. The second phase is sliding and friction stage (T2), in which the driven part has touched the active part, the dynamic friction begins to produce effects, and power driven part turning faster. When the driven part synchronizes with the active part, the second phase ends. This phase asks for shorter action time, smaller impact and less friction work. The third phase is static friction stage (T3). In this phase, friction changes into static from dynamic, the driven part and the active part begin to turn together at the same speed. The third phase asks for no skid and complete synchronization. The last phase is synchronization end stage (T4). This phase needs the rapid separation of the driven part and the active part.

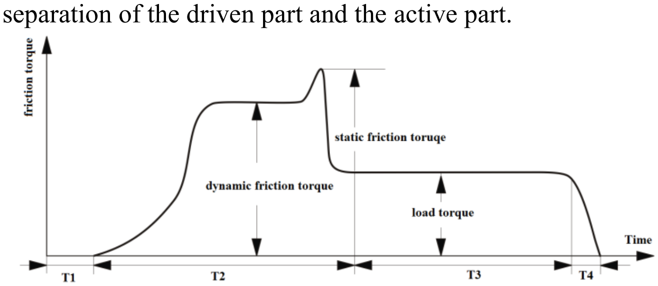


Fig.4 Characteristic curve in working process of electromagnetic synchronizer

III. Control Strategy of Synchronization Process

A. Performance Indicators of Synchronization Process

The aim of this paper is to reduce the vibration and impact when the electromagnetic synchronizer switches its state. According to the performance evaluation method of the electromagnetic synchronizer [10], this paper lists synchronization time, friction work and longitudinal jerk as performance indicators.

(1) Synchronization time. Synchronization time is the time from acceptance of synchronization command to the achievement of synchronization. From the Fig.4, we can see the synchronization time is the time of T1 and T2. From Fig.3, we can see the gap between the electromagnetic coil and armature iron is very small. So we can ignore the T1 phase, and let synchronization time equal to the time of T2.

(2) Friction work. Friction work refers to the work produced by the slid and friction between the active part and the driven part. Friction work mainly occurs in phase T2, and it can directly affect the service life of the electromagnetic synchronizer, and it is the main reason for the temperature rise. Friction work can be calculated by the formula (1).

$$W = \int T(t)\left|\omega_e(t)-\omega_c(t)\right|dt \quad (1)$$

Where $\omega_e(t)$ is the speed of the active part, $\omega_c(t)$ is the speed of the driven part, $T(t)$ is the working torque of the electromagnetic synchronizer.

According to the dynamic mechanical analysis of the electromagnetic synchronizer, the dynamic movement of the active part can be expressed as the formula (2).

$$\dot{\omega}_e(t) I_e = T_e - T(t) \tag{2}$$

Where T_e is the output torque of the engine, I_e is the rotational inertia of the active part.

For the driven part, the movement can be described as follows:

$$\dot{\omega}_c(t) I_c = T(t) \tag{3}$$

Where I_c is the rotational inertia of the driven part.

(3) Longitudinal jerk. Longitudinal jerk is the evaluation indicator of the electromagnetic synchronizer when state switching, its expression is as follow:

$$J = \frac{dV^2}{d^2t} = \frac{r}{i}\ddot{\omega}_c(t) = \frac{r}{iI_c}\frac{d(T(t))}{dt} \tag{4}$$

Where, r is the effective radius of the wheel, and i is final gear ratio of drive axle, V is the speed of the vehicle.

Longitudinal jerk directly affects ride comfort of the vehicle and service life of the power transmission system. According to the relevant laws, the value of truck's longitudinal jerk should be less than 10m/s^2, and the longitudinal jerk of passenger car should be less than 5m/s^2. So in order to control the value of the longitudinal jerk, the key is to control the change of electromagnetic torque. That means the electromagnetic torque should change smoothly in the friction stage.

B. Control Strategy of Electromagnetic Synchronizer

When design control strategy of electromagnetic synchronizer, we need to consider the working process and the performance characteristic of the electromagnetic synchronizer. This paper adopts the sectional control method as follows[11].

(1) In the T1 phase, the working torque is zero, so the drive current of the electromagnetic synchronizer should be as big as possible to shorten the time of gap elimination.

(2) In the T2 phase, the main objective is to reduce the friction work, so we choose the optimal PID control method. This method has parameter self-tuning function, and has the advantages of high reliability and robustness. Select speed difference $\omega_{ec}(t)(\omega_{ec}(t) = \omega_e(t) - \omega_c(t))$ as detection object, select angular acceleration change rate function of the driven part as restricted object, and select the friction work and longitudinal jerk as optimization object, we design the feedback control method as shown in Fig.5.

(3) In the T3 phase, the control target is static friction torque. The maximum value of static friction torque must be bigger than working torque to make sure there is no slipping between the driven part and the active part. To reduce the electrical energy consumption, and maintain static friction state, the target value of the static friction force can be determined by the product of transfer torque and its fluctuation coefficient.

(4) In the T4 phase, the aim is the driven part separates rapidly from the active part. In this phase, we can use the switch control.

According to the thinking of sectional control method, we think the controls of the T1, T3 and T4 phase are relatively simple. While the control of the T2 phase is complicated. So we choose the control of the T2 phase as the main study object, and design an optimal PID control method[12]. The flowchart of this method is shown in Fig.5.

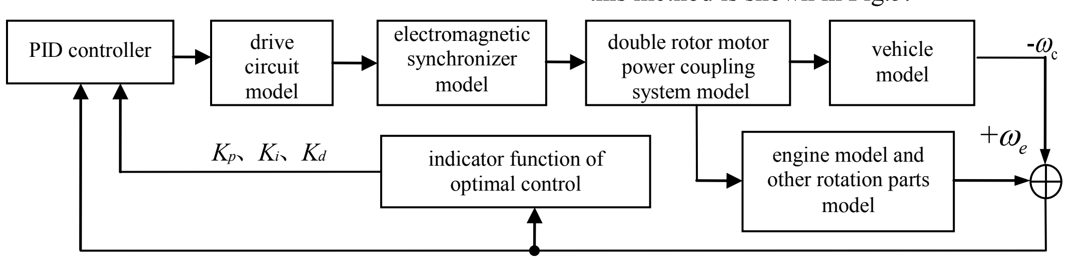


Fig.5 Control model of the optimal PID

C. Design of the Optimal Control

In the Synchronization, the frictional work and the longitudinal jerk are opposing. If the frictional work reduces, the time of state switching will shorten inevitably, the result is the longitudinal jerk increases, and the converse is also true. So in the design of the optimal control, we need to balance the two performance indicators.

Choose $x_1 = \omega_{ec}(t)$, $x_2 = T(t)$ as the state variables, choose $u = \frac{d(T(t))}{dt}$ as the controlled variable, based on the quadratic optimal control theory, the formula (1)-(4) can be changed in state space equation as follow.

$$\dot{x} = AX + BU + C \tag{5}$$

Here, $X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$, the state matrix $A = \begin{bmatrix} 0 & \frac{I_c + I_e}{I_e I_c} \\ 0 & 0 \end{bmatrix}$, the state matrix $B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$, the disturbance matrix $C = \begin{bmatrix} \frac{Te}{Ie} \\ 0 \end{bmatrix}$, the control matrix $U = [u]$.

From these, the frictional work can be expressed as follow:

$$W = \int x_1 x_2 dt \tag{6}$$

And the longitudinal jerk can be expressed as follow:

$$J = \frac{r}{iI_c} u \tag{7}$$

Consider the balance of the frictional work and the longitudinal jerk, we choose the quadratic performance functional of the optimal control system as follow:

$$\begin{aligned} L &= \frac{1}{2}\int (x^T Q x + \eta u^2)\frac{d^2\omega}{dt^2} \\ &= \frac{1}{2}\int (x_1 x_2 + \eta u^2) dt \end{aligned} \tag{8}$$

Where, the state weight matrix $Q=\begin{bmatrix} 0 & 0.5 \\ 0.5 & 0 \end{bmatrix}$, η is the weight proportion of the longitudinal jerk, its value range is between 0 and 1 in theory.

Refer to the formula (6)-(8), and use the solution of the Riccati matrix differential equation[13], we can get the optimal control locus of u. Then build the dynamics models of electromagnetic synchronizer and its drive circuit, we can calculate the value of the control electrical signal.

IV. BUILDING MODEL

A. Kinetic Model of the Electromagnetic Synchronizer

The main performance parameter of the electromagnetic synchronizer is the maximum transmission torque. According to the operation principle of the electromagnetic synchronizer which belongs to frictional synchronizer, we can know that the maximum transmission torque can be expressed as follow[14]:

$$T = \frac{1}{2}\mu R F m \tag{9}$$

Where, T is the maximum transmission torque, μ is the friction coefficient. In static friction process, μ is static friction coefficient. And when in dynamic friction, μ is dynamic friction coefficient. Besides, R is the effective radius of the annular friction surface, F is the pressing force, it is equal to the electromagnetic force of electromagnetic coil. And m *is* the number of annular friction surface.

In the static friction and dynamic friction stage, the calculation methods of R are different. When in the static friction, R can be calculated by formula (10), and when in the dynamic friction, R can be calculated by formula (11).

$$R = \frac{2(R_o^3 - R_i^3)}{3(R_o^2 - R_i^2)} \tag{10}$$

$$R = \frac{1}{2}(R_o - R_i) \tag{11}$$

Here, R_o is the excircle radius of friction torus, and R_i is the inner circle radius of friction torus.

According to the Maxwell equations, the electromagnetic force can be expressed as the formula (12) [15-16].

$$F = \frac{\phi^2}{2\mu_0 S} = \frac{B^2 S}{8\pi} \times 10^7 \tag{12}$$

Here, ϕ is the magnetic flux, S is the effective area of the armature iron, μ_0 is vacuum magnetic permeability, its value is $4\pi \times 10^{-7}$ Wb/(Am), and B is magnetic induction intensity of electromagnetic coil, which can be calculated by the formula (13) [16] .

$$B = \frac{NI}{K\delta} \times \mu_0 \tag{13}$$

Here, N is the turns number of the electromagnetic coil, I is the current of the electromagnetic coil, δ is the air gap between the electromagnetic coil and armature iron, and K is magnetic flux leakage factors.

B. Drive Circuit Model

According to the formula (9) - (13), we can know the main control parameter of the electromagnetic synchronizer is the driving current. This paper adopts the PWM method to adjust the effective driving voltage of the electromagnetic synchronizer[17], and then to control the driving current. The structure of the circuit is shown in Fig. 6.

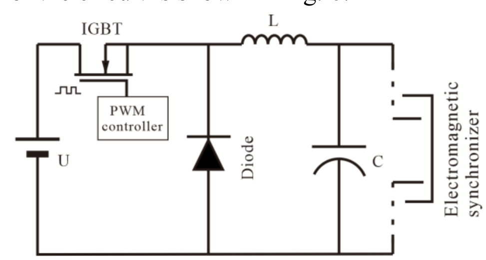


Fig.6 Drive circuit structure of electromagnetic synchronizer

Hypotheses:

(1) IGBT is the ideal element. It has the ideal performance characteristics. So its switch lag time, inductive reactance, capacitive reactance, and voltage drop will be ignored.

(2) Voltage source is ideal, and its internal resistance is zero.

(3) Electromagnetic synchronizer can be equivalent to a resistance load. Its inductance characteristic can be ignored.

According to Kirchhoff's laws, the circuit in Fig.6 can be described as follows:

$$\dot{x}_i = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{R_s C} \end{bmatrix} \begin{bmatrix} x_i \\ x_u \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} PU \tag{14}$$

$$\dot{x}_u = \begin{bmatrix} -\frac{1}{L} & 0 \\ \frac{1}{C} & -\frac{1}{R_s C} \end{bmatrix} \begin{bmatrix} x_i \\ x_u \end{bmatrix} \tag{15}$$

Where, U is the supply voltage, x_i is the current of the electromagnetic synchronizer, R_s is the equivalent resistance of electromagnetic synchronizer, and x_u is the voltage of the electromagnetic synchronizer. Besides, C, L, P are the capacitor, the inductor and the duty cycle respectively.

V. Test Result and Analysis

When we use quadratic optimal control theory to evaluate the duty ratio of the driving voltage, the value of η is the critical factor. In this paper, η is set to 0.5. This means the friction work and the longitudinal jerk have the same weight in the optimal control.

Referring to the formula above, we set up the simulation model all in Matlab/Simulink software[18]. Then execute the simulation, we can get the duty cycle's curve of the driving voltage in the whole working cycle, which is shown as Fig.7. Here, the time of T3 phase is set to 0.8s.

From the Fig.7, we can see the optimal PID control method demonstrates the four working process of the electromagnetic synchronizer wholly. In the whole working cycle, the gap eliminating time (T1) is 0.17s, the sliding time (T2) is 0.81s, and the time of ending synchronization (T4) is 0.09s.

From the Fig.7, we also can see the gap eliminating time and the ending synchronization time are both very short, and the ultimate control parameter (P) can effectively track the target value with the control of the optimal control method. On the same time the state switching process is relatively stable, the overshoot, the attenuation ratio and the recovery time are all in a good state.

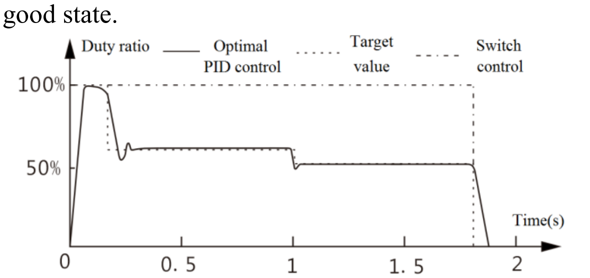


Fig.7 Control voltage duty ratio curve of electromagnetic synchronizer

From these results above, we can think the control method designed in this paper has realized the anticipated effect entirely.

Fig.8 is the speed curve of the active part (inner-rotor) and the driven part (outer-rotor). From this curve, we can see the rotating speed fluctuations of the active part and the driven part is mainly in the T2 stage. Compared with the switch control method (referring to the switch control curve in the Fig.7), the friction time of the optimal PID control method is about 0.16s longer. But rotating speed of the active part and the driven part under the control of the optimal PID is more stable, and its fluctuations is smaller.

Fig.9 is the curve of the longitudinal jerk. From this curve, we can see the maximum value of the longitudinal jerk under switch control is 6.8m/s^2, and the fluctuation amplitude is larger. But under the optimal PID control, the maximum value is 4.3 m/s^2, a big drop of 37%. Furthermore, under the optimal PID control, the maximum value of the longitudinal jerk appears at the primary stage of the sliding and friction stage, and afterward, the longitudinal jerk is small. Conversely, under the switch control, the longitudinal jerk has no obvious decrease in the first half time, only in the end of the sliding and friction stage, the longitudinal jerk begins to converge.

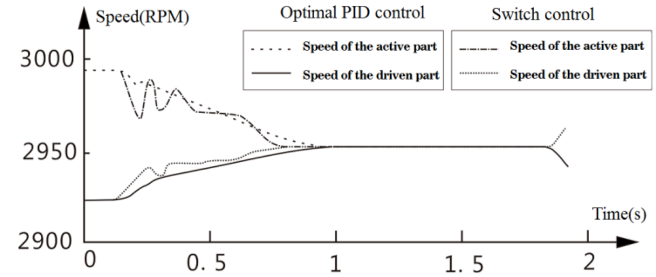


Fig.8 Speed curve of the driven part and the active part

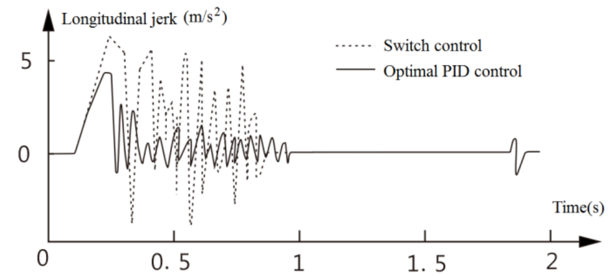


Fig.9 Curve of longitudinal jerk

Fig.10 is the friction work curve of the whole work cycle. From the figure, we can see the friction work under the optimal PID control increases by about 0.2KJ compared with the switch control method. This means the optimal PID control method can effectively balance two warring performance indicators: the frictional work and the longitudinal jerk.

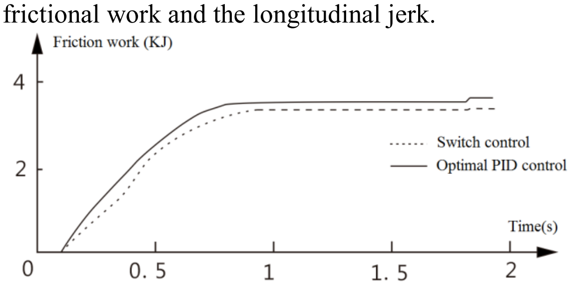


Fig.10 Curve of friction work

As was mentioned above, we can think the optimal PID control method designed in this paper is successful. And by this method, the electromagnetic synchronizer can do it job well in the double rotor motor power coupling system. It can improve the ride comfort and transmission efficiency of the hybrid electric vehicle.

VI. Conclusion

(1) This paper bases on the structure and principle of the double rotor motor power coupling system, proposes the improvement measure: add electromagnetic synchronizer between the input shaft and the output shaft. With the help of the electromagnetic synchronizer, the inner rotor and the outer rotor are connected rigidly, and the double rotor motor power coupling system can realize mechanical direct transmission. At this time, engine power can be transmitted

to the drive axle with direct mechanical joining, jumping over the electromagnetic coupling transmission of the double rotor motor power coupling system. This can improve transmission efficiency obviously.

(2) Considering the structure features and the working process of the electromagnetic synchronizer, this paper proposes the think and strategy of the sectional control method for electromagnetic synchronizer. After analysis of each stage working characteristics to the electromagnetic synchronizer, the sliding and friction phase is chosen as the main study object. Then using the two quadratic optimal control theory, we select friction work and the longitudinal jerk as the performance indicator, and set up the quadratic performance functional. From these, the optimal PID control method is designed.

(3) This paper builds the mathematical models of the electromagnetic synchronous and its control circuit. Using the models and the optimal PID control method, we simulate the working process of the electromagnetic synchronous. The simulation results show the optimal PID control method can effectively control the working process of electromagnetic synchronizer. It can balance the friction work and the longitudinal jerk, and reduce the impact when the electromagnetic synchronizer switches its state. In conclusion, to the double rotor motor power coupling system, electromagnetic synchronizer can play a significant role in efficiency improvement and the ride comfort when the vehicle is at economical speed.

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