Energy Conservation Mechanism of the EHPS in Pure Electric Bus

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Abstract
In order to study the energy conservation mechanism of the EHPS (Electric Hydraulic Power Steering), this paper builds an EHPS system experimental platform, including the master control platform, the test system module, the steering resistance hydraulic loading module and the EHPS system energy consumption. Based on the test of the energy consumption of the above major components, key factors influencing the energy consumption of the EHPS system is studied. Test results suggest that the non-steering and low-steering demands of the EPHS system have a huge influence on the overall energy consumption of the EHPS system. These research findings are of guiding significance to the development of new-type energy-saving EHPS system.
Keywords: PURE ELECTRIC BUS, ELECTRIC HYDRAULIC ASSISTING STEERING, ENERGY CONSERVATION MECHANISM

1. Introduction

Benefiting from the development of electric control and battery techniques, the pure electric bus has been studied widely as a new-energy bus in recent years [1, 2].At the same time, the hydraulic power steering system has been replaced by the EHPS system. Currently, foreign countries adjust the rotational speed of the motor by installing the EHPS system on the commercial bus so as to improve the fuel economy and the vehicle stability [3, 4]. Some domestic pure electric buses are also installed with the EHPS system, which improves the convenience of bus steering to some extent. However, most buses still adopt the hydraulic power steering system featuring a steering motor with the fixed rotational speed. This results into the laborious steering of buses at a low speed. The constant speed of the motor also results in a huge increase of the energy consumption. Therefore, it is necessary to develop a new EHPS system with better energy-saving effect and suitable for pure electric buses. The mathematic model of the EHPS system of the pure electric buses is built, and combined with the simulated AMESIM model to study the influence of the front-shaft load variations on the steering performance. Control strategies are designed to meet vehicles' requirements of ease at a low speed and good road sense at a high speed, and provide theoretic bases for installation of the EHPS with a better performance on the pure electric bus.

2. Composition and working principles of the EPHS

2.1. EHPS system structure

This research is based on the pure electric bus with the hybrid power system. The EHPS system structure mainly includes the steering wheel, the hybrid power system, the transducer, the motor, the hydraulic pump, the oil tank, the recirculating ball steering gear, the rocker, the drag link and the carriage wheel. See Fig. 1 below:

2.2. Working principles of the EHPS system

When the pure electric bus veers, the frequency divider will work out the rotational speed required by the motor according to the motor rotational speed, the shaft load, the vehicle speed and the input information of the steering wheel angular speed sensor; adjust the frequency and voltage of the input hybrid power system, and input the alternating current power supply already adjusted in terms of frequency and voltage into the motor to control the motor rotation and to further control the output flow of the oil hydraulic pump and the value of the power. The system can greatly improve the energy-saving performance of the electric hydraulic system.

3. EHPS system mathematic model

The movement force of the nut caused by the steering wheel torque equals to the acting force of the screw on the nut. Then, EHPS system can be divided into four parts, namely the manual steering gear, the motor, the steering control valve and the controller. For the convenience of study, the machinery steering gear model, the motor model, the steering control valve model and the controller model are built, respectively, and various models are connected in AMESIM for simulated analysis.

3.1. Machinery steering gear

This paper studies the circulating ball steering gear, ignoring the interval and friction of the steering system. In the model, the movement among the nut, the screw and the sector is shown in Figure 2.

According to Newton's Second Law, the force balance equation of the nut is as below:

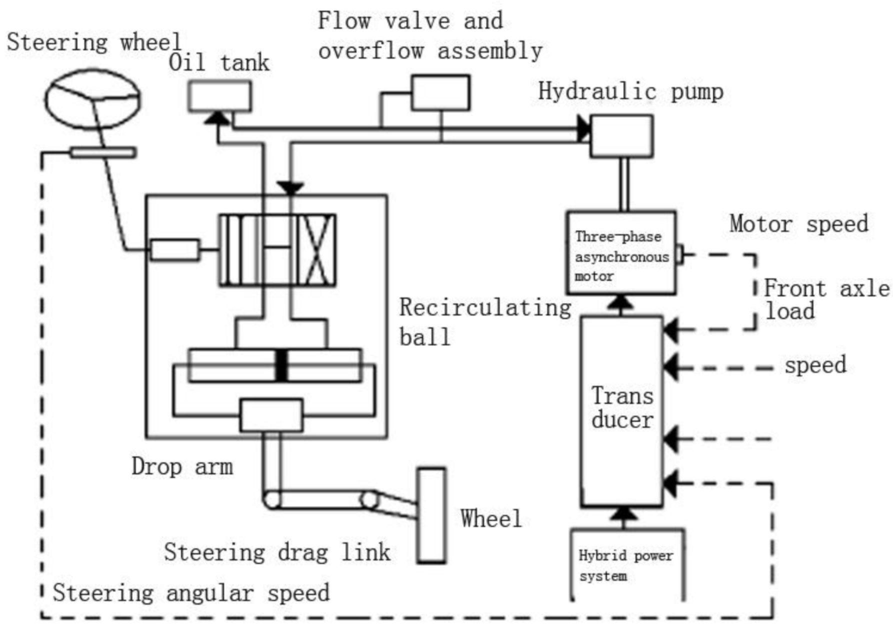

Figure 1. EHPS system structure of the pure electric bus

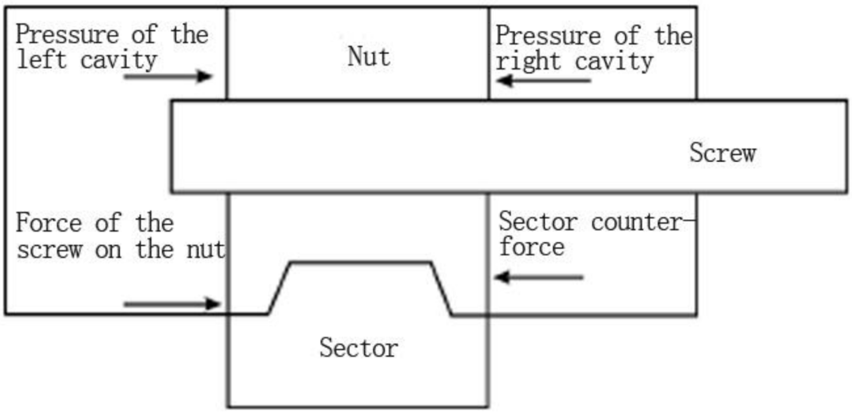

Figure 2. Movement among the screw, the nut and the sector

$$M_1 x_1 = F_1 + F_2 - F_3 - F_4 \tag{1}$$

In Eq. (1): M_1 stands for the nut mass; x_1 for the nut displacement; F_1 for the pressure of the left cavity; F_2 for the force of the screw on the nut; F_3 for the pressure of the right cavity; F_4 for the counter-force of the sector.

The transmission relationship between the nut displacement and the steering wheel steering angle is as below:

$$x_1 = \frac{s\partial}{2\hbar} \tag{2}$$

In Eq. (2): S stands for the screw lead; θ for the steering wheel angle.

The left and right cavity pressure of the power cylinder is:

$$F_1 = p_5 A, F_3 = p_6 A \tag{3}$$

In Eq. (3): p_5 stands for the pressure of the left cavity; p_6 for the pressure of the right cavity; A for the valid working area of the hydraulic oil.

3.2. Motor model

The pure electric bus adopts the three-phase asynchronous motor. Every circuit phase of the motor is shown in Figure 3.

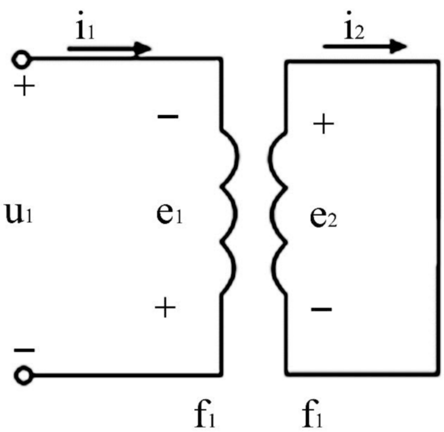

Figure 3. Every circuit phase of the three-phase asynchronous motor

The torque of the three-phase asynchronous motor generated by the interaction between the flux of every pole and the rotor current in the rotating magnetic field is shown below:

$$T = K\frac{sR_2U_1^2}{R_2^2 + (sX_{20})^2} \tag{4}$$

In Eq. (4): T stands for the electromagnetic torque of the asynchronous motor; K for relevant constants of the motor structure; S for the slip ratio; R_2 for the resistance of the rotor in every phase winding group; U_1 for the stator circuit voltage; X_{20} for the rotor inductive reactance when n=0.

Based on Eq. (5), the electromotor slip ratio can be obtained:

$$s = \frac{n_0 - n}{n_0} = \frac{60f_1 - np_i}{60f_1} \tag{5}$$

In Eq. (5): n_0 stands for the rotational speed of the magnetic field; n for the rotor speed; f_1 for the current frequency of the stator circuit; p_i for the number of poles on the motor magnetic field.

According to the moment balance principle, the motor movement equation is:

$$T = T_1 + T_2 = p_a \times q + T_2 \tag{6}$$

In Eq. (6) : T_1 stands for the machinery load torque; T_2 for the no-load loss torque; P_a for the output pressure of the hydraulic pump; q for the discharge flow of the hydraulic pump.

3.3. Steering control valve model

The steering control valve equivalent model of the EHPS system is shown in Figure 4.

According to Fig. 2-3, the flow equilibrium equation can be obtained:

$$Q_{in} = Q_1 + Q_2, Q_1 = C_d A_1 \sqrt{(2/p)(p_{in} - p_{5)}}$$

$$Q_5 = Q_1 + Q_4, Q_2 = C_d A_2 \sqrt{(2/p)(p_{in} - p_6)}$$

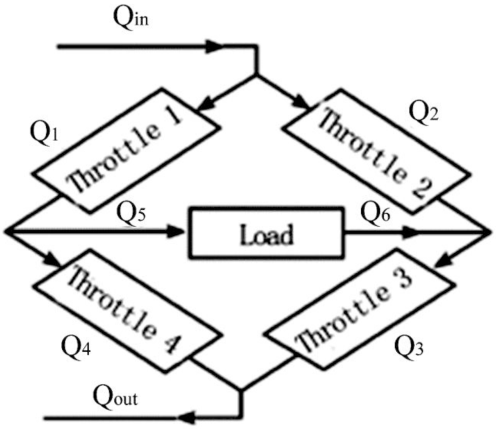

Figure 4. Rotary steering control valve equivalent model

$$Q_6 = Q_3 - Q_2, Q_3 = C_d A_3 \sqrt{(2/p)(p_6 - p_{out})}$$

$$Q_{out} = Q_3 - Q_2, Q_3 = C_d A_3 \sqrt{(2/p)(p_6} - p_{out}) \quad (7)$$

In Eq. (7), Q_{in} and Q_{out} stands for the oil inflow and outflow quantity of the steering valve, respectively; Q_i (1, 2, 3, 4) for the flow of the throttle valve, i; C_d for the flow coefficient; A_i(1, 2, 3, 4) for the throttling area throttle valve, i; p for the hydraulic oil density; p_{in} and p_{out} for the oil inflow and outflow pressure of the steering valve.

3.4. Controller model

The transducer in the EHPS system receives the input signals of the front-shaft load sensor. First, the maximum rotational speed of the steering motor is confirmed. According to it, the motor rotational speed of the bus during straight driving can be obtained. When the bus veers, the transducer will work out the rotational speed required by the motor according to the rotational wheel angular speed, and quickly and accurately achieve the target rotational speed for the motor through the PID control [10]so as to change the value of the power on a real-time basis, and improve the energy-saving performance. According to different front-shaft loads, the segmentation fitting is employed to explore the relationship of the motor rotational speed with the vehicle speed and the steering wheel rotational speed. Those are the cubic spline interpolation graph of the relationship among the three when the front-shaft load is 47,500N and 70,000N [11].It can be simplified into the function relationship expression, namely motor speed=f (front-shaft load, vehicle speed and steering wheel angular speed). The front-shaft load is within the range of 64,400~70,000N.

4. EHPS system simulation and results analysis

Take the EHPS system of a 12m pure electric bus for example. The EHPS system simulation model is built in AMESIM [10].

4.1. Analysis of the low-speed steering power characteristics

Assume that the steering wheel torque shows sinusoidal variations. The frequency is 0.2Hz, and the amplitude is 12.5m. Fig. 5 is the power characteristic curve of different front-shaft loads at the speed of v=10km/h. It can be seen that: with the increase of the steering wheel torque, the hydraulic power also increases gradually. When the steering wheel torque is fixed, the higher the front-shaft load is, the higher the hydraulic power provided by the EHPS system is, so as to improve easiness of steering of the bus at a low speed.

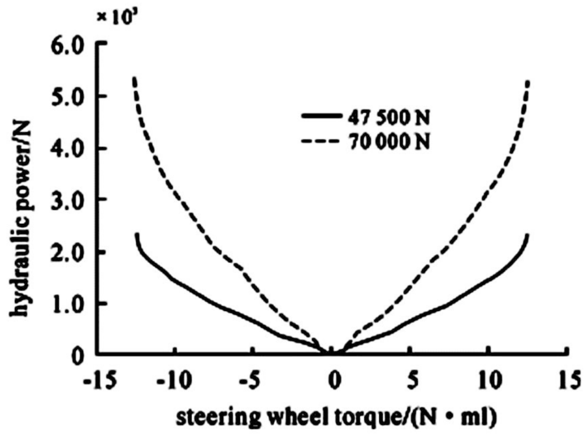

Figure 5. Steering power characteristic when the front-shaft load is 47,500N and 70,000N, respectively at v=10km/h

4.2. Analysis of the steering energy-saving performance

Assume that the steering wheel torque is the step signal input. When the step signal input is 12.6N.m. and the bus speed is v=10km/h, different front-shaft loads are corresponding to different motor power consumption. During steering, the bus EHPS system will control the motor output rotational speed according to real-time changes of the front-shaft load. From Fig. 6, it can be seen that, when the steering wheel torque is fixed, the smaller the front-shaft load is, the smaller the motor power consumption is. Therefore, the EHPS system considering the front-shaft load changes can improve the rotational energy-saving performance. At the same time, the motor response time is within 0.2s, suggesting that the EHPS system can meet the requirement of fast power speed response.

5. EHPS system energy conservation and results analysis

5.1. Composition of the test stand system

The establishment of the test stand is mainly to study the energy consumption of the EHPS system. The test standard adopts the modularized de-

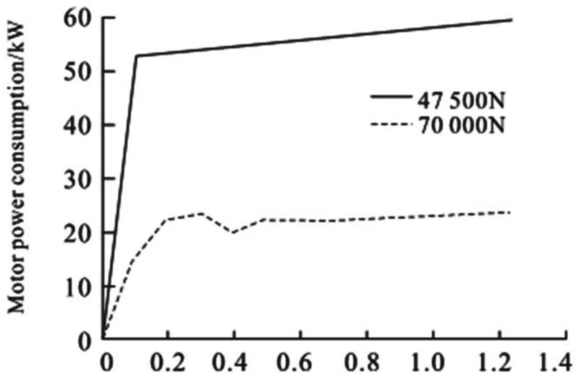

Figure 6. Motor power consumption when the front-shaft load is 47,500N and 70,000N, respectively, and at the speed of v=10km/h

sign method. The EHPS system test stand platform is made up of the major EHPS test control platform, the EHPS system, the steering resistance load module (simulated according to the overall dynamic model, and the steering resistance is provided by the hydraulic loading system) and the test module.

5.2. Basic working principles

The EHPS system test platform is input with the steering signal through the steering wheel. The steering resistance load module will provide corresponding steering resistance according to the angular speed and the speed signals provided by the test module. At the same time, the test module collects the data of various test points in the EHPS system for data analysis.

5.2.1. Steering resistance load module

The steering resistance load module is used to simulate the real-time steering resistance according to the driving speed and the steering speed. (See Fig. 2) Currently, the domestic steering test stand generally adopts the spring load style. The load style boasts the advantages of simple structure and low cost. However, since the spring's elasticity coefficient cannot be adjusted on a real-time basis, the steering resistance under various steering situations cannot be accurately simulated. In order to overcome the above limits, the simulation test stand adopts the hydraulic load system. The shaft resistance generated by the load oil cylinder is directly added to the output end of the power oil cylinder of the EHPS system. The displacement sensor is used to confirm whether the steering wheel can return to the meso-position. The press sensor is used to test the value of the resistance imposed on the rack. During steering, the major test control platform of the EHPS system works out the steering resistance according to the practical operation situations, namely the steering wheel angle, θ, and the vehicle speed, V, and transmits it to the hydraulic load control unit. The pressure control valve and the proportional direction valve are controlled for the sake of controlling the pressure and flow of the load hydraulic cylinder so as to achieve the change of the steering resistance along with the change of the operation situations [6].

5.2.2. Test module

The EHPS system test stand test module is mainly used to collect the output pressure, flow, temperature signals, steering wheel angular speed, steering angle, torque signal, tension and pressure of the power oil cylinder, displacement signals, rotational speed of the brushless DC motor and current signal, and to control the steering resistance. (Fig. 8) The master control platform features the Industrial Personal Computer. The test data collection software is developed by the virtual instrument.

5.3. Analysis of the test results

Due to the function requirements of the steering system, the steering system flow should be maintained even if there are no steering conditions. (Open central steering valve) The reason is that operators might need steering at any time.

5.3.1. Motor current consumption under the given hydraulic resistance

Fig. 8 is a relationship chart between the motor current consumption and the hydraulic pump output flow when an EHPS system power unit is used to overcome an invariable hydraulic resistance, P = 0.2MPa. From the above chart, it can be seen that, with the increase of the motor rotational speed (namely the increase of the output flow), the consumption of the motor current increases in line with the quadratic curve. If the hydraulic resistance keeps increasing, the current might be higher (such as the lengthening of the connecting line, the change of the oil viscosity, the change of the throttling area of the steering valve, etc.).

5.3.2. Influence of the system backpressure on the current consumption under different output flows

Fig. 9 shows the influence of the hydraulic system's backpressure on the corresponding current consumption under different output flows.

Under the non-steering situation, the value of the motor current has a huge influence on the energy conservation of the steering system. The low-steering demands accounts for more than 90% of the steering cycle. The energy conservation mechanism of reducing the motor current consumption through the reduction of the power unit's rotational speed (flow) or the reduction of the hydraulic losses (use of the low-leakage valve and shortening of the inflow and outflow oil

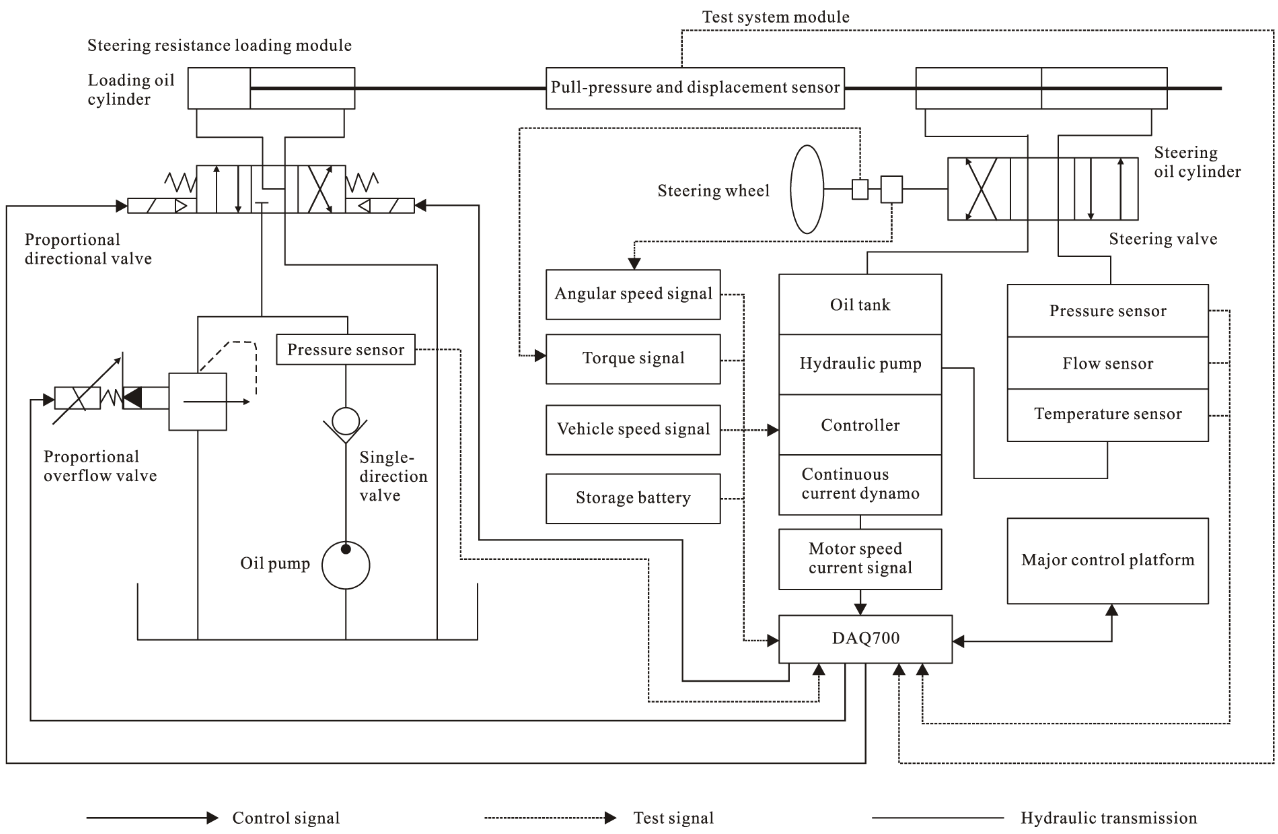

Figure 7. Test stand steering resistance load module and test system module

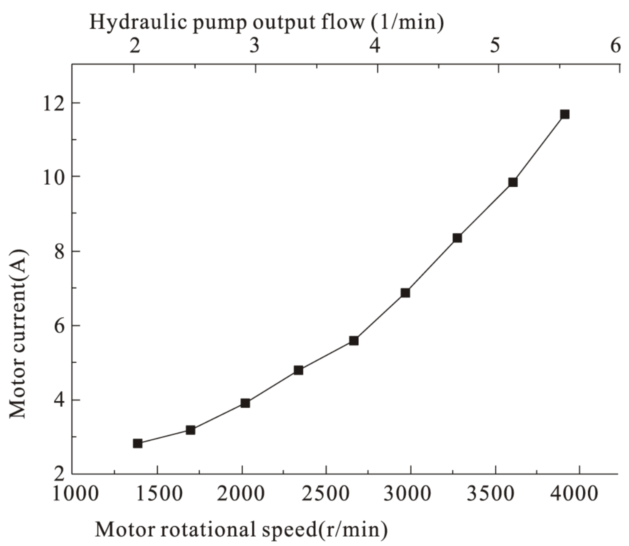

Figure 8. Relationship between the current consumption and the output flow under the given hydraulic resistance

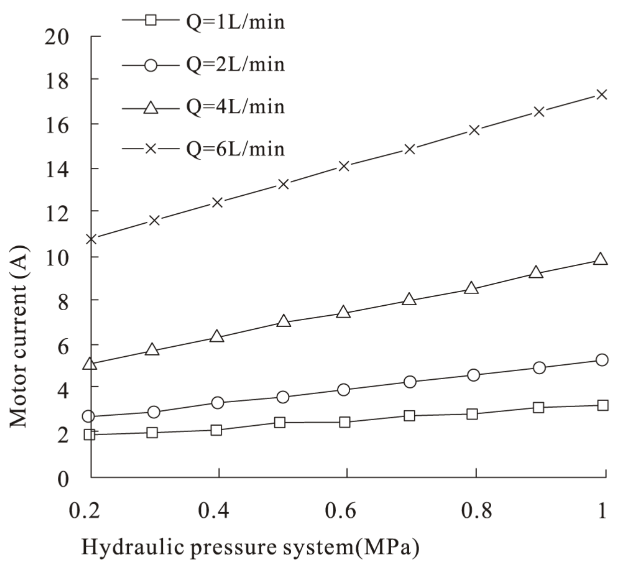

Figure 9. Influence of the system backpressure on the current consumption under different output flows

pipe length, etc.) is fully feasible. During the practical steering cycle, the energy consumption of the EHPS system mainly concentrates on the non-steering and low-speed steering situations. To the EHPS system, the power consumption is decided by the standby energy consumption. To reduce the low-speed steering and the non-steering energy consumption by studying the rapid exchange rules between the non-steering situation and the low-speed steering situation of the EHPS system is the major research objective of this paper.

6. Conclusions

This paper builds a simulation model of the EHPS system of the pure electric bus according to the system composition and mathematic model, designs the control strategies and conducts a simulation analysis of the power characteristics, energy-saving performance and response performance of the bus under different front-shaft loads. The energy-saving experiment suggests that the EHPS system of the pure electric bus can change the power characteristic in response to different front-shaft loads, succeeding in improving the steering easiness and energy-saving performance, and providing theoretical bases for the development of new EHPS system products.

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