Design and Implementation of Controller for EHPS of Intelligent Electric Bus

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ABSTRACT In order to meet the needs of bus electrification and intellectualization, a controller for the steering power system of an intelligent electric bus is studied in this paper. The contents mainly include: based on the structural principle and control strategy of the EHPS system, Luenberger observer is designed, which is applied to the sensorless control system of PMSM. Then, a controller with STM32F103zet6 chip as its core is designed and manufactured. The hardware design of the controller includes the minimum system circuit, power supply circuit, signal acquisition circuit, integrated driver module circuit, CAN communication circuit, fault and high temperature alarm circuit of the single chip computer; combining the design of each hardware part, the controller of EHPS system is made. In the aspect of software implementation, the control decision-making part, a motor drive control part, fault diagnosis, and transmission part are mainly designed. Finally, the bench test and vehicle test of the controller are carried out. The purpose of the bench test is to test the control effect of the controller on the motor. The bench test results show that the target speed response of the motor is fast and the output is stable. The controller developed in this paper realizes the control of PMSM. The purpose of the real vehicle test is to test whether the controller meets the actual application requirements of the steering power system of the vehicle. The actual vehicle test results show that the steering wheel’s torque decreases obviously, and the steering power system has good power-assisting performance when the EHPS system controller works. With the increase of vehicle speed, the power-assisting torque decreases accordingly. EHPS system realizes the dynamic change of power-assisting and meets the requirements of the conventional power-assisting mode of the car. In addition, the controller can realize the active steering control by controlling the electric power assistant device, which provides a platform for the realization of lane auxiliary maintenance, automatic parking, unmanned driving, and other functions.

INDEX TERMS Automotive engineering, electronic hydrostatic power steering, sensorless control system, Luenberger observer, intelligent electric bus, PMSM.

I. INTRODUCTION
Steering system is the mechanism that keeps direction a vehicle or changes the direction of a vehicle according to the driver’s manipulation. It directly affects the vehicle's handling stability, active safety and driver’s comfort [1]. Power steering system is an important part of advanced driving assistant system. It provides the vehicle with the help of light steering at low speed and stable steering at high speed [2]. The power steering system is also an important means to realize automatic steering of intelligent vehicles in the future [3]. Although it is extremely difficult to achieve unmanned driving in all vehicles on the road for a short period of time, 100% of driverless cars have become a reality in some environmentally controlled applications such as factories, warehouses, and farms [4], [5]. As far as the necessity and feasibility of unmanned driving is concerned, the bus is likely to be the first vehicle to realize unmanned driving on public roads. It has the characteristics of fixed area, high frequency and high cost. In terms of feasibility, the bus’s travel route is relatively fixed, and the high-precision map can be used repeatedly for repeated use [6]. Similarly, the fixed route can also obtain better security protection [3]. In terms of necessity, the drivers of bus are generally professional drivers, who are engaged in vehicle driving for a long time. The fatigue driving situation of bus drivers is often much...
more serious than that of common cars. The cause of many passenger car accidents is the driver’s fatigue driving or other improper operations [7]. Therefore, the use of reliable automatic driving technology can improve the safety of passenger driving. It is of great significance to study the automatic steering technology of bus.

There are two kinds of power steering systems commonly used in vehicles: Electrical Power Steering (EPS) and Electronic Hydraulic Power Steering (EHPS). EPS system is directly assisted by booster motor, and its system performance is directly affected by the performance of booster motor [8]. Early EPS system mainly used DC motor as booster motor. With the development of motor technology, permanent magnet synchronous motor (PMSM) and AC induction motor were also successfully applied to EPS system [9]. TRW has developed the EPS system for commercial vehicles and studied the EPS system for heavy trucks and buses. Saifia et al. designed EPS non-linear controller by using fuzzy control method, basing on BDCM and considering the limitation of motor input current [10]. For the intelligent bus steering system, EPS is limited by the power and size of motor due to the excessive demand for steering power. At present, the commercial bus EPS system is less used, and EHPS system is more used in buses [11]. The Servotronic EHPS system manufactured by ZF Company has been assembled and used on hybrid buses developed by bus manufacturer Solaris [12]. The EPHS-Gen C system developed by TRW has been used on light and medium commercial vehicles of Mercedes-Benz’s Sprinter series and Ford’s Transit model [13]. Yu and others designed a new type of commercial vehicle EHPS. The system coordinated the motor and the opening of solenoid valve to realize the steering power control of commercial vehicle. Moreover, a new type of electronically controlled hydraulic steering test rig has been built for test verification [14]. Daimler Buses develop a new fully integrated EHPS system and explained the system is used currently in buses with gross weights exceeding 7.5t. With the progress of motor and electronic control technology and the rapid development of unmanned driving technology, EHPS system is more suitable for passenger cars’ steering booster system than EPS system. Research and development of EHPS controller for bus, optimization of steering assist characteristics and realization of automatic steering are important directions for future development of driverless technology.

In order to improve the dynamic steering performance and space utilization of steering assist system for medium and heavy vehicles, a controller based on the STM32 chip for the steering power system of intelligent electric bus is studied in this paper. The main contents include the design of PMSM sensorless control system, the hardware design and software design of EHPS system controller, and the test of the controller. Firstly, based on the structure principle and control strategy of EHPS system, Luenberger observer is designed and applied to sensorless control system of PMSM. Secondly, the hardware design of the controller includes the minimum system circuit, power supply circuit, signal acquisition circuit, drive integrated module circuit, CAN communication circuit, fault and high temperature alarm circuit of the single chip computer. In the aspect of software, the control decision-making part, motor drive control part, fault diagnosis and transmission part are mainly designed. Finally, the bench test and vehicle test of the controller are carried out. The test includes motor performance test and real vehicle test, which verifies the control effect of controller on the motor and the effect of vehicle power assistance.

II. STRUCTURE AND CONTROL STRATEGY OF EHPS SYSTEM

A. STRUCTURE AND WORKING PRINCIPLE OF EHPS SYSTEM

Traditional EHPS system drives steering oil pump by motor. Under the control of controller, EHPS provides steering power of suitable size and more stable for the whole vehicle steering system according to vehicle speed signal and steering wheel angular speed signal [15]. The structure of EHPS system mainly consists of steering gear, oil storage tank and other traditional HPS components, as well as controller, rotary valve, gear oil pump and so on. The working principle of EHPS system is as follows: EHPS system controller receives start signal, vehicle speed signal, turning angle signal and other signals through CAN bus. When the vehicle is turning, the electronic control unit calculates the appropriate motor speed based on the received expected angle signal and the vehicle speed signal. Then the motor drives the hydraulic pump to work, which increases the oil pressure in the oil pipeline and realizes the steering power of the vehicle through the movement of the steering piston. The working principle of EHPS system is shown in Fig. 1.

![FIGURE 1. Working principle of electric hydraulic power steering system.](image-url)
rotating space vector as the reference coordinate, the stator current is decomposed into two orthogonal components and controlled separately. Vector control is widely used because of its good low-speed performance and high debugging accuracy [17].

In order to control PMSM, it is necessary to detect the rotor position and speed at all times. At present, the commonly used detection methods are resolver sensor detection method, Hall sensor detection method, sensorless detection method and so on [18]. Both of resolver sensor and Hall sensor use mechanical sensors to detect the position of the rotor. The sensors are susceptible to the working environment and have high cost. Therefore, the sensorless algorithm of calculating the position and speed of the motor by using the easily available physical quantities of the motor has attracted wide attention. In this paper, the sensorless vector control method is used to control the PMSM of steering assist.

1) PMSM SENSORLESS CONTROL SYSTEM

At present, the sensorless control methods of PMSM mainly include extended Kalman filter, sliding mode observer, Luenberger observer, extended Kalman filter and so on. Extended Kalman filter can filter noise and has good anti-jamming ability, but the algorithm is complex and requires high hardware performance [19], while the sliding mode observer has chattering problem [20]. Therefore, the sensorless vector control algorithm of PMSM based on Luenberger observer is adopted in the controller designed in this paper.

A block diagram of the PMSM position sensorless vector control system based on the Luenberger observer is shown in Fig. 2. The control system uses voltage and current to estimate the opposing electromotive force $e_a$ and $e_\beta$ of the motor. Then, by using the relationship between rotor position, speed and opposing electromotive force, the $\theta_r$ (rotor position) required for the inner loop of the double closed loop control system can be calculated, and the input $\omega_r$ of the speed outer loop is also calculated. The control system uses three PI regulators and SVPWM to control the operation of the motor.

2) OBSERVER DESIGN

The PMSM voltage equation is as follows:

$$U_a = R_i i_a + P \Psi_a$$ \hspace{0.5cm} (1)

$$U_a = R_i i_a + P \Psi_a$$ \hspace{0.5cm} (2)

$$U_c = R_i i_c + P \Psi_c$$ \hspace{0.5cm} (3)

$U_a$, $U_b$ and $U_c$ are three-phase winding voltages of PMSM in a-b-c coordinate system. $R_s$ is stator resistance, and $i_a$, $i_\beta$, $i_c$ are three-phase currents respectively. $p$ is the motor pole logarithm. $\Psi_a$, $\Psi_\beta$, $\Psi_c$ are three-phase stator flux respectively.

Equation (1) (2) (3) is transformed into a$\theta$ coordinate system, and equation (4) (5) is obtained by positioning the a-axis on the $\alpha$-axis (Clarke transformation):

$$V_\alpha = R_s i_a + \frac{d \Psi_a}{dt}$$ \hspace{0.5cm} (4)

$$V_\beta = R_s i_\beta + \frac{d \Psi_\beta}{dt}$$ \hspace{0.5cm} (5)

In the equation, $L_S$ stands for the stator inductance of the motor, $i_a$, $i_\beta$, $V_\alpha$, $V_\beta$ are the stator winding current and voltage in the stator two-phase stationary coordinate system, $\Psi_a$, $\Psi_\beta$ stands for the stator flux in the two-phase stationary coordinate system, $\Phi_m$ is the flux, $\omega_r$ is the rotor speed, and $\theta_r$ stands for the rotor electric angle. Among them:

$$\theta_r = \omega_r t$$ \hspace{0.5cm} (6)

The flux linkage equation (5) is substituted into the voltage equation (4), and the following equations (7) is obtained.

$$V_\alpha = R_s i_a + L_s \frac{di_a}{dt} + \Phi_m \omega_r \cos (\omega_r t)$$

$$V_\beta = R_s i_\beta + L_s \frac{di_\beta}{dt} - \Phi_m \omega_r \sin (\omega_r t)$$ \hspace{0.5cm} (7)

The parameters $i_a$ and $i_\beta$ in the voltage equation cannot be measured directly. In addition, the motor is fully controllable, and the motor input and output can be easily obtained. Therefore, the state observation model of the motor is established, and the state quantities $i_a$ and $i_\beta$ are estimated based on the input and output values of the motor observation system. The motor state model is as follows:

$$\dot{x} = f(x(t), u(t))$$

$$y(t) = g(x(t))$$ \hspace{0.5cm} (8)

The equation of state of the motor is as follows:

$$\frac{di_a}{dt} = - \frac{R_s i_a}{L_s} - \frac{\Phi_m}{L_s} w_r \cos (\omega_r t) + \frac{V_\alpha}{L_s}$$

$$\frac{di_\beta}{dt} = - \frac{R_s i_\beta}{L_s} + \frac{\Phi_m}{L_s} w_r \sin (\omega_r t) + \frac{V_\beta}{L_s}$$

$$\frac{d\theta_r}{dt} = w_r$$ \hspace{0.5cm} (9)

Among them, the state vector: $X = [i_a i_\beta \theta_r]^T$, the input vector: $U = [V_\alpha V_\beta]^T$, and the output: $Y = \theta_r$. 89402

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Figure 2. Block diagram of vector control system with Luenberger observer.
Therefore, the motor state model is non-linear. Two new state variables are introduced below.

\[
\begin{align*}
\dot{e}_a &= \Phi_m p w_r \cos (p w_r t) \\
\dot{e}_\beta &= -\Phi_m p w_r \sin (p w_r t) \tag{10}
\end{align*}
\]

Assuming that mechanical variables change much more slowly than electrical variables, we can obtain the following equation (11).

\[
\begin{align*}
\frac{d i_\alpha}{dt} &= \frac{-R_i i_\alpha}{L_s} - \frac{e_\alpha}{L_s} + \frac{V_a}{L_s} \\
\frac{d i_\beta}{dt} &= \frac{-R_i i_\beta}{L_s} - \frac{e_\beta}{L_s} + \frac{V_\beta}{L_s} \\
\frac{d e_\alpha}{dt} &= p w_r e_\beta \\
\frac{d e_\beta}{dt} &= -p w_r e_\alpha \tag{11}
\end{align*}
\]

The motor state equation can be linearly expressed as follows:

\[
\begin{align*}
\dot{x} &= Ax(t) + Bu(t) \\
y(t) &= Cx(t) \tag{12}
\end{align*}
\]

Among them, the state vector: \( X = [i_\alpha \ i_\beta \ e_\alpha \ e_\beta]^T \), the input vector: \( U = [V_a \ V_\beta]^T \), and the output: \( Y = [i_\alpha \ i_\beta]^T \). The motor state model is shown in Fig. 3.

The Luenberger state observer of PMSM is further established after the motor state model is established. The observer model is as follows:

\[
\begin{align*}
\dot{\hat{x}}(t) &= Ax(t) + Bu(t) + K(y - \hat{y}) \\
\hat{y}(t) &= C\hat{x}(t) \tag{13}
\end{align*}
\]

The finishing equation (14) can be obtained as follows:

\[
\begin{align*}
\frac{d\hat{i}_\alpha}{dt} &= -\frac{R_i \hat{i}_\alpha}{L_s} - \frac{\hat{e}_\alpha}{L_s} + \frac{V_a}{L_s} + K_1 (\hat{i}_\alpha - i_\alpha) \\
\frac{d\hat{i}_\beta}{dt} &= -\frac{R_i \hat{i}_\beta}{L_s} - \frac{\hat{e}_\beta}{L_s} + \frac{V_\beta}{L_s} + K_1 (\hat{i}_\beta - i_\beta) \\
\frac{d\hat{e}_\alpha}{dt} &= p w_r \hat{e}_\beta + K_2 (\hat{i}_\alpha - i_\alpha) \\
\frac{d\hat{e}_\beta}{dt} &= -p w_r \hat{e}_\alpha + K_2 (\hat{i}_\beta - i_\beta) \tag{14}
\end{align*}
\]

The overall framework of the observer is shown in Fig. 4. At this time, the observer is a continuous system. According to the motor state model and the Luenberger state observer model, the feedback value of the estimated current \((i_\alpha, i_\beta)\) is introduced and discretized, and the sampling time is set to \( T \), and the following results are obtained:

\[
\begin{align*}
\hat{i}_\alpha (K + 1) &= \hat{i}_\alpha (K) - \frac{R_i T}{L_s} \hat{i}_\alpha (K) + \frac{T}{L_s} V_a (K) \\
+ K_1 T (\hat{i}_\alpha (K) - i_\alpha (K)) - \frac{T}{L_s} \hat{e}_\beta (K) + \frac{T}{L_s} V_\beta (K) \\
\hat{i}_\beta (K + 1) &= \hat{i}_\beta (K) - \frac{R_i T}{L_s} \hat{i}_\beta (K) + \frac{T}{L_s} \hat{e}_\alpha (K) + \frac{T}{L_s} V_\beta (K) \\
+ K_1 T (\hat{i}_\beta (K) - i_\beta (K)) - \frac{T}{L_s} \hat{e}_\alpha (K) + \frac{T}{L_s} V_a (K) \\
\hat{e}_\alpha (K + 1) &= \hat{e}_\alpha (K) + K_2 T (\hat{i}_\alpha (K) - i_\alpha (K)) \\
+ p w_r \hat{e}_\beta (K) T \\
\hat{e}_\beta (K + 1) &= \hat{e}_\beta (K) + K_2 T (\hat{i}_\beta (K) - i_\beta (K)) \\
- p w_r \hat{e}_\alpha (K) T \tag{15}
\end{align*}
\]

After obtaining the two components of the back electromotive force, the rotor position angle and speed are calculated by using the phase locked loop. The block diagram of the phase locked loop is shown in Fig. 5. Phase locked loop obtains the rotor speed \( \omega_r \) of the motor through the reconstruction and calculation of the PI regulator, and the rotor position \( \theta_r \) is obtained. The PI regulator causes the entire rotor position estimation system to form a closed loop, and \( \omega_r \) and \( \theta_r \) are locked.

By the definition of \( e_\alpha, e_\beta \), let \( A = \Phi_m p w_r \), equation (16) is derived.

\[
\begin{align*}
\hat{e}_\alpha (K T) &= A \cos (\hat{\theta}_k) \\
- \hat{e}_\beta (K T) &= A \sin (\hat{\theta}_k) \tag{16}
\end{align*}
\]
Then the final result is as follows:

\[-\hat{e}_a (KT) \sin (\theta_{K-1}) - \hat{e}_b (KT) \cos (\theta_{K-1}) = \hat{\theta}_k - \theta_{K-1} \]

(17)

Finally, using the designed Luenberger observer, the rotor speed and position information of the PMSM can be estimated, which effectively solves some of the drawbacks of the traditional sensor, and the algorithm is simple and easy to implement.

### III. HARDWARE DESIGN OF EHPS SYSTEM CONTROLLER

#### A. HARDWARE CIRCUIT FRAMEWORK OF EHPS SYSTEM CONTROLLER

The core of the controller is STM32F103zet6 MCU. The chip is a 32-bit ARM microcontroller. It is produced by ST Company, and the core is Cortex-M3. Starting from the functional requirements of EHPS system, the hardware circuit of the controller mainly includes the minimum system of single-chip computer, power module, signal acquisition module, integrated driver module, CAN communication module, fault and high temperature alarm module, etc. The minimum system of single-chip computer is the basis of the normal operation of the circuit. The power module mainly provides the working power for the chip, power driver module and CAN communication module. The signal acquisition module includes acquisition circuit of bus voltage and three-phase current, which are used for hardware protection, software protection, the estimation of motor speed and rotor position. The hardware circuit structure of the controller is shown in Fig. 6.

#### B. HARDWARE DESIGN

1) **MCU MINIMUM SYSTEM CIRCUIT**

The minimum system circuit of single chip computer includes clock circuit, reset circuit, download circuit, debugging circuit and so on. The circuit is shown in Fig. 7.

Stm32F103zet6 has two external clock circuits, one is high-speed clock and the other is low-speed clock. The reset circuit is a manual reset circuit, which allows the program to be executed from scratch at any time. The download circuit takes Sanyo’s USB bus adapter chip CH340G as the core. It can download the program by connecting the PC terminal with the data line. The debugging circuit is used to check whether the microcontroller is working properly when debugging.

2) **CAN COMMUNICATION MODULE**

Stm32f103zet6 has built-in CAN communication controller. Start signal, speed signal and steering control signal in CAN of vehicle can be obtained through CAN-BUS transceiver. Error information and working condition can also be sent to CAN of vehicle through CAN-BUS transceiver. The CAN-BUS transceiver uses JTA1050 high-speed transceiver produced by NXP Company. The transceiver has a wide common-mode range differential receiver and high electromagnetic immunity, and the electromagnetic radiation of transceiver is very low. The circuit of CAN communication module is shown in Fig. 8.

3) **SIGNAL ACQUISITION MODULE**

The signal acquisition module mainly includes bus voltage acquisition and three-phase current acquisition. The collected three-phase current and bus voltage are mainly used for motor speed estimation and rotor position estimation, as well as undervoltage protection and overcurrent protection. Voltage acquisition is based on resistor voltage divider and capacitor filter. Current acquisition is based on RC filtering by selecting appropriate sampling resistors. Three-phase current acquisition circuit is shown in Fig. 9 and bus voltage acquisition circuit is shown in Fig. 10.
4) INTEGRATED DRIVER MODULE
The controller uses IGCM15F60GA driver integration module produced by Infineon Company. The circuit diagram is shown in Fig. 11. Its three-phase bridge consists of six IGBTs. And the integrated module integrates drive, control, detection, drive circuit and protection circuit of over-current, over-heat, over-voltage. It not only reduces the volume of the system and development time, but also greatly enhances the reliability of the system. IGCM15F60GA has a maximum bus voltage of 400V, a peak current of 15A, a switching frequency of 20kHz, working temperature range of $-40 \sim 125^\circ$ and a working voltage of $14V \sim 18.5V$.

5) POWER MODULE
The power module mainly converts 24V power supply into stable voltage to supply power to each module. Firstly, 24V power supply is converted into 15V supply integrated power module by integrated voltage regulator LM2596. Then the
6) FAULT AND HIGH TEMPERATURE ALARM MODULE

Fault alarm module is mainly composed of buzzer and LED lamp. The small lamp is driven by single chip computer. The buzzer is driven by S8050. When the communication fails, the buzzer will alarm. When the controller temperature is too high, the LED will be off at 0.5 second intervals to remind the temperature is too high. The fault and high temperature alarm module circuit is shown in Fig. 13.

C. MANUFACTURE OF CONTROLLER CIRCUIT BOARD

Combining the above hardware design, the EHPS system controller is produced, as shown in Fig. 14. The control board integrates control and drive, meets the requirement of high integration of booster motors in the current market, and greatly improves the space utilization rate.

IV. SOFTWARE DESIGN OF EHPS SYSTEM CONTROLLER

A. PROGRAM TOTAL PROCESS DESIGN

The program consists of three parts: control decision-making part, overheat protection program design part, motor drive control part. Main program flow chart as shown in Figure 15.
First, the program initializes I/O port, timer, AD, CAN communication, and then detects whether the CAN communication is normal. If the CAN communication fails, the program stores the fault code and starts the fault alarm, and the system enters the no-steering power mode. If the CAN communication is normal, the program will continue to check whether the controller is normal. If the controller is faulty, the fault code will be sent to the vehicle network through the CAN communication module, then the fault alarm will be started and the system will enter the no-steering power mode. When the controller is normal, the program detects whether the vehicle starts or not; if the vehicle has started, the program starts the motor after receiving the steering signal, and the vehicle is not started, the program will always detect the vehicle status; the program returns to the status of vehicle detection stage after the steering stop.

**B. MOTOR DRIVE CONTROL PROGRAM DESIGN**

After receiving the steering signal, the motor starts, and the acquisition module starts to collect three-phase current ($i_a$, $i_b$, $i_c$) and bus voltage ($u_f$). $u_\alpha$ and $u_\beta$ are obtained by coordinate transformation between three-phase current and bus voltage. $u_\alpha$ and $u_\beta$ calculate the switching time of the three-phase bridge by using SVPWM, and then the MCU outputs six PWM signals to the power module. Finally, the controller outputs the three-phase electric drive motor, and the flowchart of the motor control program is shown in Fig. 16.

**C. OVERHEAT PROTECTION PROGRAM DESIGN**

STM32f103zet6 has an internal temperature sensor that can be used to measure CPU and surrounding temperature. The internal temperature sensor is connected with the internal ADCx_IN16 input channel, which converts the output voltage of the sensor into digital value. The temperature sensor supports a temperature range of $-40^\circ$ to $125^\circ$. The controller detects the temperature every 2 seconds. If the temperature of the controller exceeds $60^\circ$, Software will startup interruption, the system enters no-steering power mode, and the controller sends the overheat signal to the vehicle network. Flow chart of controller overheat protection program as shown in Fig. 17.

**V. TESTING**

**A. BENCH TEST**

In order to verify whether the manufactured controller is driving the PMSM normally, a bench test is performed on the motor equipped with the controller. The testing bench is based on the motor performance testing platform to test the motor. In addition, the testing bench includes a developed EHPS system controller, a 1.5kW PMSM, a CAN communication box, and a personal computer. The layout of the bench is shown in Fig. 18. From left to right, there are computers, CAN communication boxes, controllers, PMSM, couplings, test equipment and motor performance testing platform.

This test is an open-loop test. The computer simulates the steering wheel angle signal of the vehicle, then the steering signal is sent to the EHPS system controller through CAN communication tool. The motor starts and then drives the coupling to rotate. After the motor controller gets the steering signal, the motor starts and then the motor drives the coupling.
to operate the test equipment. Test equipment starts testing by running coupling. At the computer end, the calculation program inside motor performance testing platform can obtain the parameters data of the motor running, including the motor speed, output power, torque and so on. The test set three target speeds of the motor, 400 r/min, 500 r/min and 600 r/min respectively. After the test, the speed data of the motor were obtained from the test system, and the data were plotted as a graph. The change curve of the speed of the motor with time was shown in Fig. 19.

From the data in the Fig. 19, it can be concluded that the test vehicle can complete the basic operation under the controller and the state is stable in about 0.15s after starting. Therefore, the developed EHPS system controller drives PMSM normally and the sensorless vector control method is effective, which can meet the basic functions of the EHPS system.

**B. VEHICLE TEST**

In order to verify whether the EHPS system controller developed in this paper meets the requirements of practical use of steering power system, the EHPS system controller is tested in real vehicle. The test vehicle is Howard JK6660GBEV pure electric bus, which is an automatic driving test vehicle equipped with automatic steering device and environmental awareness system. The test vehicle and test arrangement are shown in Fig. 20. The controller is loaded in the front hood of the vehicle. Data acquisition of vehicle position signal, steering wheel angle signal, torque signal and so on uses NI company’s cDAQ9178 data acquisition equipment. The physical object of the equipment and the compiled acquisition program are shown in Fig. 21. Due to the limited conditions, only the power steering road test in the in-situ steering condition and the low-speed working condition was carried out, and the low-speed automatic steering road test was also carried out.

1) **POWER STEERING ROAD TEST**

The main purpose of the power steering road test is to compare the steering wheel torque before and after the vehicle is equipped with the EHPS system. First, the tester drives the experimental car to the site. When the position is not moving and there is no steering assist, the steering wheel is rotated clockwise to the limit, and the counterclockwise rotation is also rotated to the limit, and the collected steering wheel data is recorded; then the steering assist is turned on, the steering wheel is rotated clockwise to the limit, and the counterclockwise rotation is also reversed to the limit, and the collected
steering wheel data is recorded; finally, the vehicle is driven at a speed of 10 km/h, and the same operation is performed like the in-situ steering condition, and the collected steering wheel data is recorded. The test data are sorted out and plotted as a curve, as shown in Fig. 22.

The following conclusions can be drawn from the experimental images. When the power steering road test in the in-situ steering condition, the maximum steering wheel torque is 47.13 N·m when the controller is not working (non-steering assist); the maximum steering wheel torque is 9.32 N·m when the controller is working (steering assist); the maximum difference between them is 37.81 N·m. When the power steering road test in the low-speed working condition, the maximum steering wheel torque is 31.62 N·m when the controller is not working (non-steering assist); the maximum steering wheel torque is 7.84 N·m when the controller is working (steering assist); the maximum difference between them is 23.78 N·m. Therefore, when the EHPS system controller developed independently works, the torque of steering wheel is obviously reduced. With the increase of vehicle speed, the steering assistant moment decreases and the dynamic change of assistant force is realized.

2) AUTOMATIC STEERING ROAD TEST

The main purpose of the low-speed automatic steering road test is to test the automatic steering performance of vehicles equipped with EHPS systems. Firstly, the test vehicle is driven to the site. The target trajectory is a simple single lane change and travels at a low speed of 10 km/h and 20 km/h. Then the computer sends the expected corner signal to the controller, Controller drives the steering assist system to work. When the power steering system works, no one controls the steering wheel. During the test, the steering wheel angle signal and vehicle position signal collected by the acquisition equipment (angle sensor, GPS of Vehicle) are recorded. Finally, the test data are sorted out and plotted into curves. The steering wheel angle curve is shown in Fig. 23 and the vehicle trajectory curve is shown in Fig. 24. The experimental image shows that the actual trajectory of the vehicle is a single lane change, and the steering wheel angle changes smoothly. The vehicles can use EHPS system to realize automatic steering without relying on external force to operate steering wheel.

From the above actual vehicle tests, it can be concluded that the steering power system with the controller can realize the active control of the bus steering system, and the automatic steering is stable. In addition, the controller of intelligent electric bus EHPS can make the power assist system have good steering power performance at low speed. The goal of assisting force changing with speed was achieved, and the driving feel was improve. Compared with the traditional...
steering power system, the system has dynamic power and more stable power changes.

VI. CONCLUSION
Based on STM32F103zet6 main control chip, a EHPS system controller for intelligent electric bus is developed in this paper. From the test results, the following conclusions can be drawn:

1) The hardware and software of the controller work normally, and can receive the speed and angle signals from the CAN bus. The communication between the MCU and the CAN bus is realized. The hardware of the controller integrates control and drive, which meets the requirement of high integration of the booster motor in the current market and greatly improves the space utilization rate.

2) The controller adopted the sensorless vector control algorithm based on Luenberger observer, which reduced the wiring harness connection and manufacturing cost under the premise of guaranteeing power limitation, and the controller can drive the permanent magnet synchronous motor to work normally, the control effect is stable, and it can achieve the basic function of EHPS system.

3) The power steering system with the controller has good steering performance when it works, and achieves the goal of power steering varying with speed. When the vehicle status information is known, the controller can receive the corner signal to control the booster device to realize the active control of the bus steering system, achieve the purpose of automatic steering. And the automatic steering is stable, a platform for the realization of the future electric bus driverless function is provided.

REFERENCES
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