Intelligent Dynamic Wireless Charging System for Electric Vehicle

Ning Wang, Qingxin Yang, Minpeng Cai and Xiaodong Bai

***Abstract*—**The paper proposes a dynamic wireless charging system for electric vehicle that provides convenience during the charging process. Multiple unipolar rectangular coils are used as the transmitters. Finite-element analysis of the dynamic wireless charging system is performed using COMSOL. The transmitters and receiver size are changed to analyzed the variation of the coupling coefficient. STM32 microprocessor is utilized, and the system functions design is provided which considers practical application. A service platform for dynamic wireless charging based on the IOV is constructed, which includes mobile phone client and network server. Google map is used to realize the functions, such as location, charging road display, path planning, navigation, start or finish charging request, payment. MySQL database is utilized to save the information of charging road and user data. A prototype is constructed according to the designed coupling structure and system parameters. Experiment results indicate that the service platform achieves the functions such as accurate positioning of EV, finding the wireless charging roads nearby, path planning, charging coil switching, billing.

***Keywords*—**electric Vehicles, dynamic wireless power transfer, internet of vehicle, dynamic charging.

I. Introduction

WIRELESS power transfer (WPT) effectively avoids direct connection of electric-equipment and power grid. It has the advantages such as flexible, secure, and dependable. Wireless power transfer overcomes the problems that instability of electrical contact, limitation of moving electrical equipment and so on [1]. Dynamic wireless power transfer technology realizes the EV charging while it's working which raises the transporting efficiency [2]. It prolongs the endurance mileage of EV and reduces the number of battery packs. Imagine if the number of wireless charging roads increased, people could build the wireless charging roads or areas every few kilometers and regard that as a petrol station, users drive into the roads rapidly and charge their EV which is working when the battery runs low.

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A GA is proposed to tune the parameters of a PID controller taking various objectives (fitness) functions into consideration, to achieve a controller with optimal performance [3]. An implantable biological monitoring system is proposed, which uses WPT and data communication technology to observe the state of implantable system in real time through the tablet computer [4]. But it only applies to the wireless charging of a single road, with the rapid development of sensor, communication and the IOV technology. The IOV is the fusion of vehicle and wireless network which is consisted of the positioning, speeding, driving direction and surroundings [5]. The integrated platform not only provides the more accurate available charging infrastructures distribution for EV owners, but also helps the utilities to evaluate the reliability or efficiency of the power grid impacted by the EV charging activities [6].

In practical applications, the transmitter end and receiver end usually require information interaction, to determine the charging requirements at the receiving end. It is also a necessary function for the system to know the power of the receiving end and billing the charging. In the case of WPT, the problem is existed, such as the receiving end should be charged or not, the quantity of charging, working conditions of the system. The paper presents an intelligent WPT system based on STM32 microprocessor. It has functions such as identification and verification, power statistics and billing, information display and interaction. And also, a service platform for electric vehicle dynamic wireless charging based on the IOV is put forward that enhances wireless charging convenience. The service platform includes mobile phone client and network server. It realizes the functions of EV pinpointing, finding the wireless charging roads, path planning, charging coil switching and billing.

II. Electric Vehicle Wireless Charging System

A. System Block Diagram

System of EV wireless charging includes road electric energy transmitting system and EV energy receiving system. Road energy transmitting system mainly consists of transmitting power conversion device, compensating network, transmitting coil, controller and hurl-slices switch etc. In order to avoid unnecessary losses and magnetic leakage problems which caused by the global power supply of long guide rail transmission coil. Charging roads are sequentially composed of multiple types of the same general of planar coils [7]. The appropriate power supply management strategy is added to the power transmission system, which only provides power to the coil under the trolley that reduces the leakage of magnetic field and coil loss. The vehicle-mounted electric energy receiving system is composed of receiving coils, compensating network, receiving end device of conversion of electrical energy, vehicle-mounted battery pack, as shown in the figure 1.

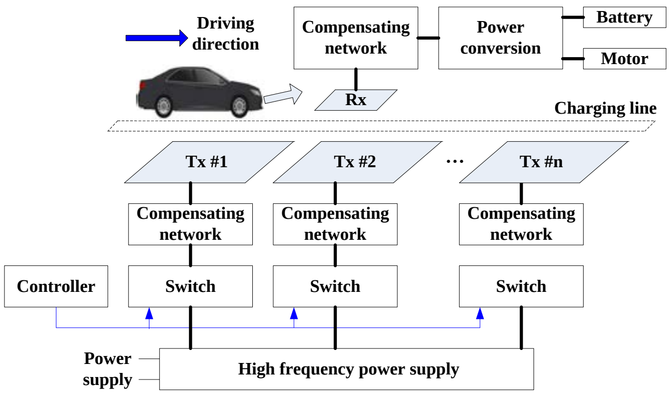

Fig. 1. System block diagram of DWPT

B. Characteristic Analyses

From figure 1, it can be concluded that the transmitting coil has two states: power-on and power-off. The power-on is the working state for power transmission, and the power-off is the stopping state for power transmission. Therefore, these two typical states can represent a series of multiple coils [8].

The optimized LCC compensation topology shows more robust power characteristic against variation of coupling factor, thereby helping maintain effective power transfer in dynamic charging application and largely enhancing the systematic controllability [9].

Equivalent circuit of the dynamic wireless power transmission system with two coils and primary-side LCC compensation network is shown in figure 2.

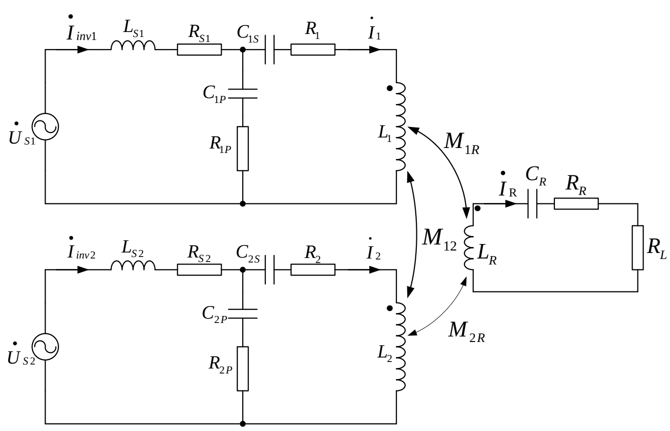

Fig. 2. Equivalent circuit of DWPT

$\dot{U}_{S1}$ is the equivalent output voltage source of the power-on circuit inverter. $\dot{U}_{S2}$ is the equivalent output voltage source of the power-off circuit inverter. R_L is equivalent load resistance. L_1, L_2, and L_R are self-inductances of power-on coil, power-off coil and receiving coil. Respectively, C_{1S} and C_{2S} are primary-side series compensation capacitances, C_R is load-side series compensation capacitance. R_1, R_2, and R_R are overall stray resistances of power-on coil, power-off coil, receiving coil and their series compensation capacitances, respectively. C_{1P}, C_{2P} and R_{1P}, R_{2P} are primary-side parallel compensation capacitances and their stray resistances. L_{S1} and L_{S2} are primary-side series compensation inductances; C_{S1} and C_{S2} are used to adjust the reactance of converters' ac side, because the inductances of L_{S1} and L_{S2} are not easily changed after forming; R_{S1} is sum stray resistance of L_{S1} and C_{S1}, R_{S2} is sum stray resistance of L_{S2} and C_{S2}. M_{12} represents mutual inductance between power-on coil and power-off coil, M_{1R} represents mutual inductance between power-on coil and receiving coil; M_{2R} represents mutual inductance between power-off coil and receiving coil. These three parameters are not shown in the figure 2. $\dot{I}_1$, $\dot{I}_2$, and $\dot{I}_R$ are currents in power-on coil, power-on coil and receiving coil. Respectively, $\dot{I}_{inv1}$ and $\dot{I}_{inv2}$ are converter ac-side currents. The power-on coil, its corresponding compensation network, and converter are named together as power-on unit; the power-off coil, its corresponding compensation network, and converter are named as power-off unit; the receiving coil and its corresponding compensation network are named as load unit.

The power and efficiency of DWPT are calculated and given by

$$\begin{cases} P_O = \mathrm{Re}(I_R)^2 * R_L \\ \eta = \dfrac{\mathrm{Re}(I_R)^2 * R_L}{\mathrm{Re}(\dot{U}_{S1} * \dot{I}_{inv1}) + \mathrm{Re}(\dot{U}_{S2} * \dot{I}_{inv2})} \end{cases} \quad (1)$$

C. Design of coupling coil

In the process of dynamic wireless charging system, the method of segmental switching was adopted in the transmitting end. Finite-element analysis (FEA) simulations are performed using COMSOL to determine the self-inductances and the coupling coefficients of the coils. The front and 3-D view of the coil structure are shown in figure 3.

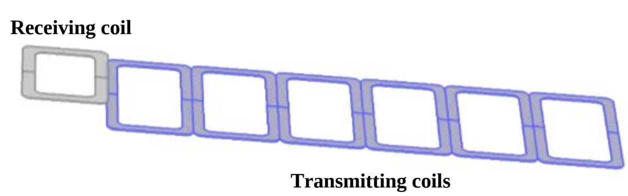

Fig. 3. Front view of the transmitters and receiver

Changing the size of the coupling coils, the optimum coil size is obtained by simulating the left-right deviation and different horizontal displacement of the receiver coil.

L and W represent the width of the transmitter coil and the receiver coil respectively.

Case 1: the receiver coil and the transmitting coil center are symmetric. d is the distance along Y axis. The wider the transmitter coil, the smaller the d change. The simulation data are shown in figure 4.

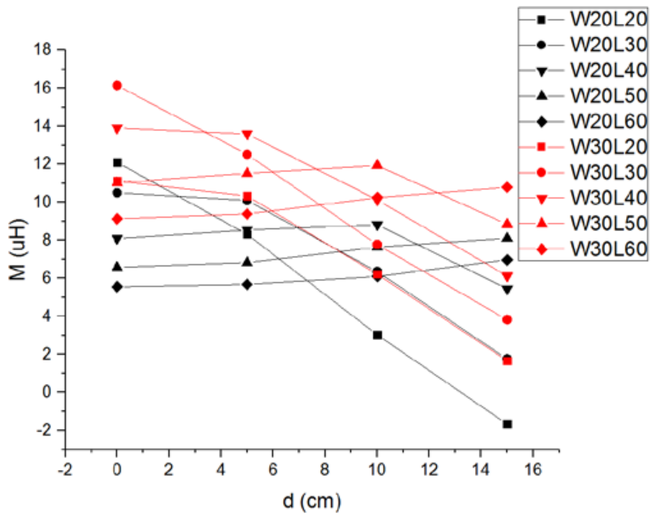

Fig. 4. M in different left-right deviation

Case 2: the right edge of the receiver coil is chose to the left edge of the transmitter coil. The longer the transmitter coil, the smaller the p change. The simulation data are shown in figure 5.

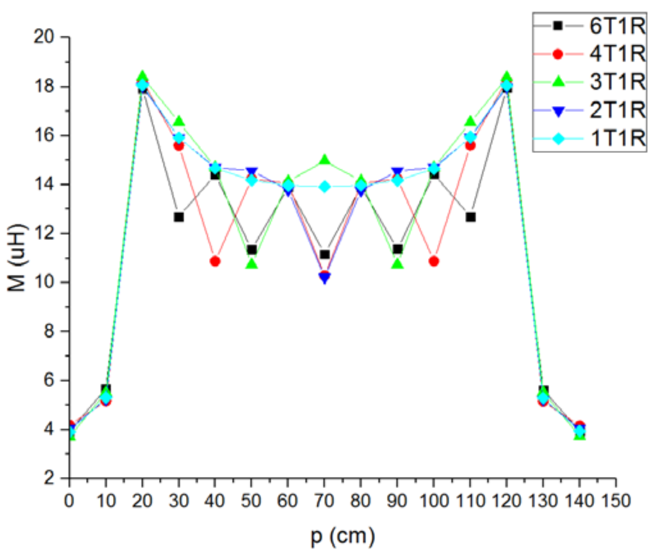

Fig. 5. M in different horizontal displacement

D. Design of control unit

STM32 is the main control module of the transmission control unit, including power acquisition module, ZigBee communication module, RFID module, LCD display module and power module. It is shown in figure 6.

STM32103RCT6 is adopted. The chip communicates with the ZigBee module through the serial interface, reading the RFID module's data information through the common IO interface, controlling relays through the universal IO interface, controlling the whole bridge inverter through PWM output interface, reading the LCD touch command via the touch screen interface.

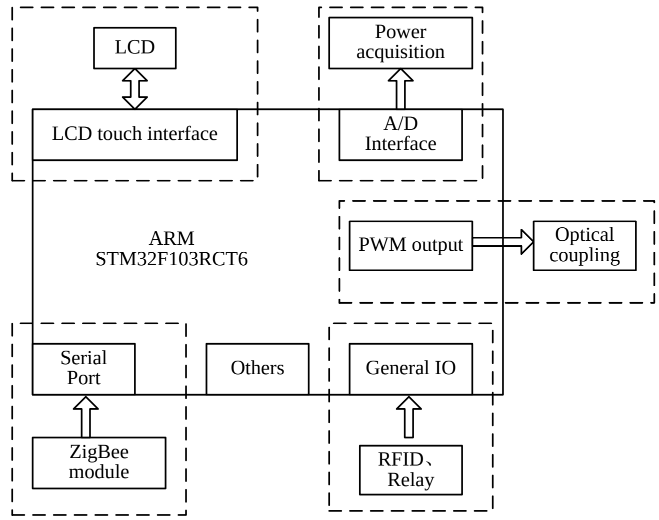

Fig. 6. Diagram of transmission control unit

E. Identification and authentication

In the intelligent WPT system, when the receiving end enters the effective power supply area of the transmitter, it initiates the authentication request to the transmitter control unit. After verification, the charging request is initiated according to the status of the transmitter. The specific workflow is shown in figure 7.

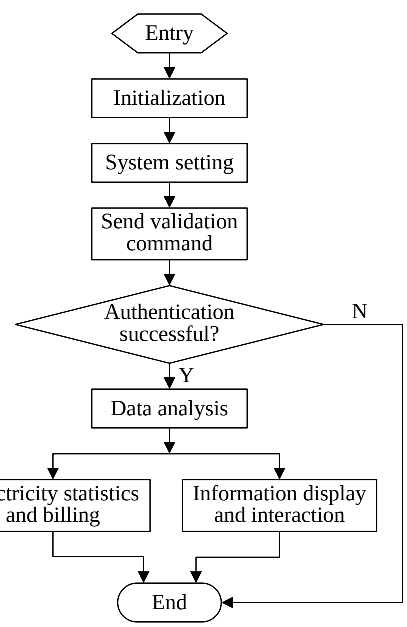

Fig. 7. System workflow

RFID technology uses the radio frequency signal to realize non-contact information transmission through spatial coupling, realizing identification through the information conveyed. But the communication distance of RFID technology is short, and the label accurately put. Therefore, ZigBee wireless communication technology is adopted in this paper. The technology has the advantages of low complexity, self-organization and low power consumption.

The identity ID on the receiving end is set to 8-bit binary number, which is compared the ID of the transmitter control unit. If equal, the successful signal is verified through validation and feedback. If it is not equal, the charging operation cannot be performed. The ZigBee data transmission format of the design is shown in table 1.

Tab. 1. Format of frame data

Frame header	Data	Check bit	Frame end
2bits	8bits	3bits	3bits

The information of the frame header is the type of the data. 01 represents the authentication information, and 00 represents the quantity information. The 8bits data represents the identity information or the actual amount of electricity.

The voltage and state of charge of a Li-ion battery is not a function, and it is usually estimated by polynomial fitting. This design adopts one fitting and two fitting methods, and the fitting result is shown in figure 8. Obviously, the effect of one fitting is better.

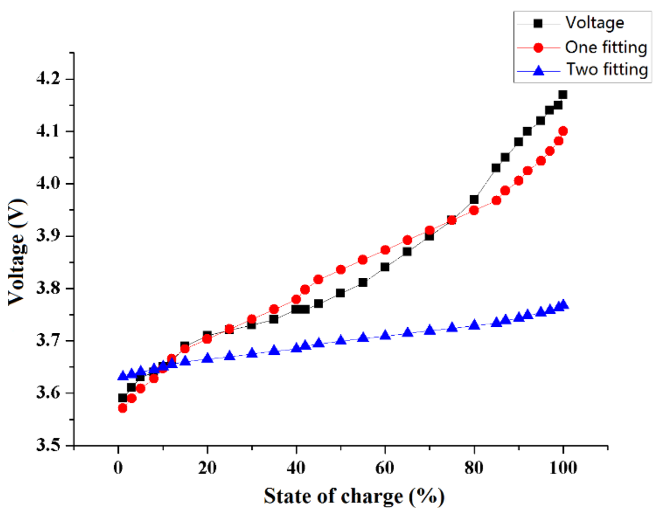

Fig. 8. Fitting curve of voltage and residual electricity

F. *Power statistics and billing*

The transmission efficiency of WPT cannot reach 100%, so the charge should be based on the actual amount received by the receiving end. The collection of system voltage is realized by using the 12-bit ADC of STM32. It can be implemented in single, continuous or scanning mode, and the results of the transformation are stored in a 16-bit data register. The maximum conversion rate is 2.4MHz, or 0.41us. When the voltage is collected, the voltage of the battery is adjusted to between 0 and 3.3V. Therefore, in the program, the real voltage value is calculated and obtained by using the relational expression.

Electricity charge is realized by RFID radio frequency card. MFRC522 is a highly integrated non-contact read and write card chip, integrated with all types of passive non-contact communication modes and protocols for 13.56MHz. The workflow is shown in figure 9.

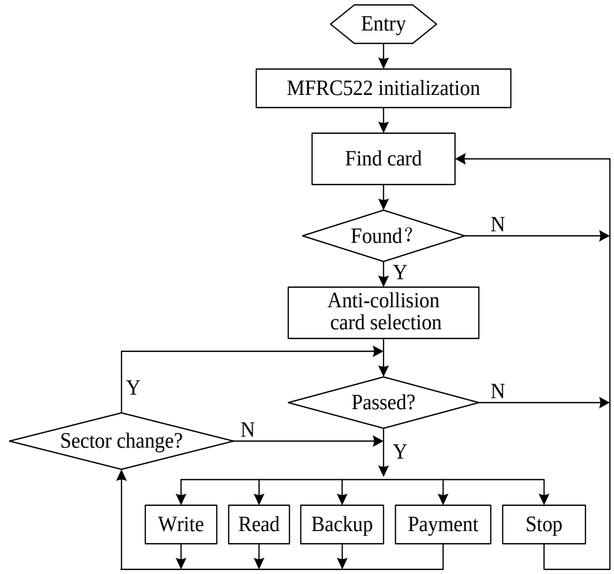

Fig. 9. Workflow of MFRC522

G. *Information display and interaction*

Human-computer interaction module is a tool for information interaction between system and users, which Is an important part of the monitoring system. This paper uses LCD touch screen to display charging voltage, current and power, and its working process is shown in figure 10.

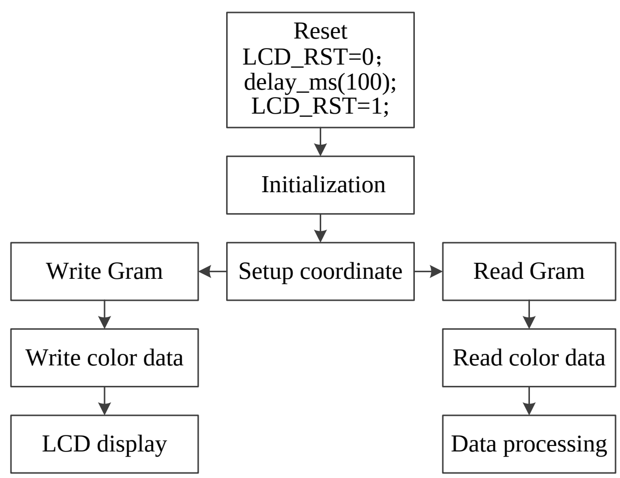

Fig. 10. Workflow of TFT LCD

III. Service Platform of The IOV

A. *Block Diagram of the IOV*

The Internet of Vehicle (IOV) is the application of IOT in the automobile industry. The network architecture of the IOV which is the basis of automotive mobile internet according to the function it can be divided into three layers [10]: the perception layer, the network layer and the application layer, as is shown in figure 11.

1) The Perception Layer

The perception layer of the IOV mainly refers to perceive the vehicle's driving state by using various intelligent sensors, readers, GPS, video camera and other physical devices in order to obtain the data of vehicle information as well as the data of location, battery capacity, etc. This design uses electrical sensor to collect the dump energy of vehicle-mounted battery. The system will send out charging notification when the battery is running low. GPS or BDS are used for collecting the location of EV.

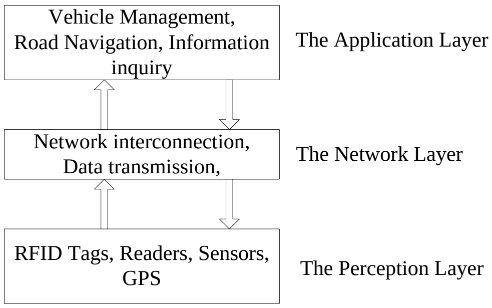

Fig. 11. System block diagram of the IOV

2) The Network Layer

The network layer realizes the two-way transmission of data, uploading the information to the application layer and transmitting the command information to the perception layer. The network layer realizes wireless communication or information interaction among the vehicle-road-person-network-environment-infrastructure. This design uses 4G network to upload the request of wireless charging and location information. Meanwhile, according to the command of the application layer, power transmission system of road is opened and it realizes wireless charging.

3) The Application Layer

The application layer collects data from the network, and analyzes, calculates and stores them. Then it provides intelligent driving, emergency rescue system, intelligent traffic management, in-car interconnection entertainment and other appropriate services. According to the functions, the application layer is divided into two part: network server and mobile phone client. This work focuses on the construction of network server and the design of mobile phone client.

B. Design of Mobile Phone Client

According to the actual requirement of EV dynamic wireless charging, the mobile phone client should have these functions like path planning, charging request sending, charging stop and billing and so on. The system frame diagram of APP, as is shown in figure 12.

1) Location: The current position of EV can be obtained through positioning technology, and is marked on the map. The location information can be updated in real time.

2) Charging road display: The road which supplies the service is marked on the map. The charging road is distinguished from the ordinary by color.

3) Path planning: When the user selects the charging path, the path planning can be made according to the user's current location and destination location. The user can choose the appropriate path according to the actual situation.

4) Charging Events: After EV arriving the charging road, the user can start charging, and finish charging.

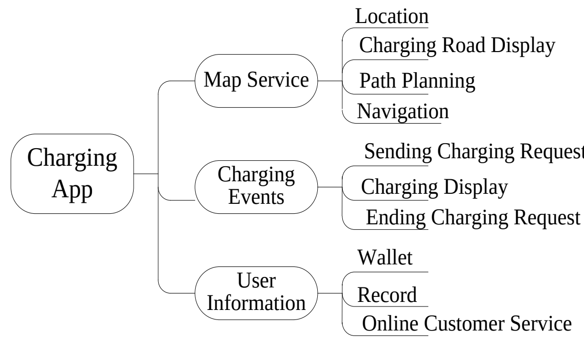

Fig. 12. System frame diagram of APP

5) Billing: The user pay the charging fee with the online payment platform.

At present, Google Map, Baidu Maps and Amap provide services of mobile phone. Google Map provides a rich API, that any developer can easily introduce the map into the applications of their own. Therefore, this design uses the Google Map. The phone client gets information of vehicle location, uploading to the server by the network connection, getting the charging road information with a POI matching algorithm and displaying on the map. It will display the path planning of charging road after booking. EV will start charging when the APP send charging request after reaching the charging road, and the system will automatic clear fee after stop charging request is sent. The client also contains a user interface menu which is used for managing balances, historical charging information, and so on.

C. Server Design

The software adopts the architecture of C/S (Client/Server), which reasonably allocates the task to Client and Server, that reduces communication overhead of system, and the client must be installed to proceed management operation. Considering the stability and cost of system, the server adopts LAMP environment configuration, Linux system adopts Ubuntu 12.04, the database adopts MySQL which is free, and the programming language adopts PHP. Setting up a database on the server that is used for saving the information of charging line and user data.

The system requires high real-time performance, and the client and server communicate via WebSocket. WebSocket is a new network protocol based on TCP, which implements full-duplex communication between the browser and the server. The data interchange format between client and server adopts JSON (JavaScript Object Notation). JSON is a lightweight data-interchange format, whose data is stored and represented in a text format completely independent of the programming language. The client starts the data interaction after establishing the connection with the server, and send the information to server through a “post” way. A complete data exchange process is: The client sends the information to the server, such as its location information, charging request information, etc. The information is converted to JSON, which is analyzed, saved, and returned to the client.

IV. Experimental Results Analysis

As mentioned above, the prototype is shown in figure 13.

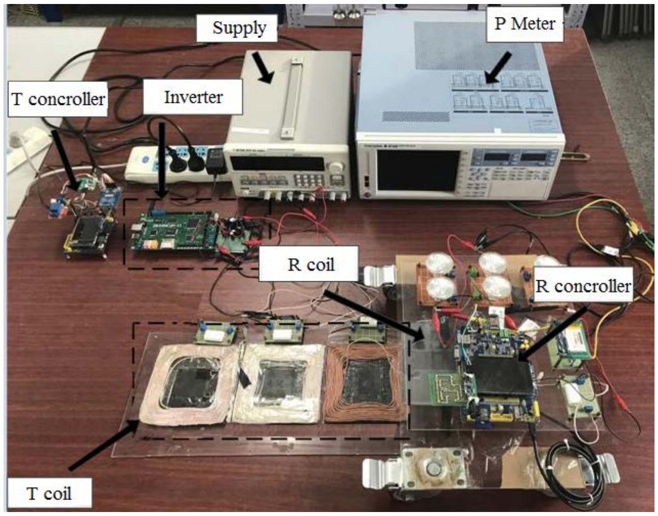

Fig. 13. Experimental prototype

A. Information display and interaction

The receiving control unit sends identity information through the ZigBee wireless network. The transmission control unit verifies the ID, and the verification is successful, as shown in figure 14.

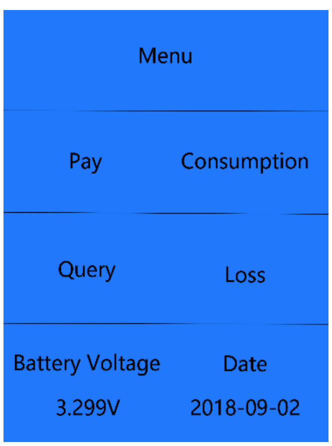

Fig. 14. Initialization interface of control unit

B. Power statistics and billing

Users can consume according to their charging requirements. The system can realize recharge, consumption, inquiry and loss of the function. After the success of the consumption, the LCD screen display card balance of the transmission control unit, and the relay is closed and the system enters the wireless charging state, as shown in figure 15.

During the charging process, the receiving control unit conducts real-time data interaction with the mobile phone through the Wi-Fi module. After the data is received by the mobile phone, the relevant information of the vehicle is displayed through the corresponding algorithm, as shown in figure 16.

When the receiving control unit detects that the battery voltage reaches the floating charging pressure, it sends the charging end signal to the launch control unit, then the transmission control unit disconnects the relay and the charging ends.

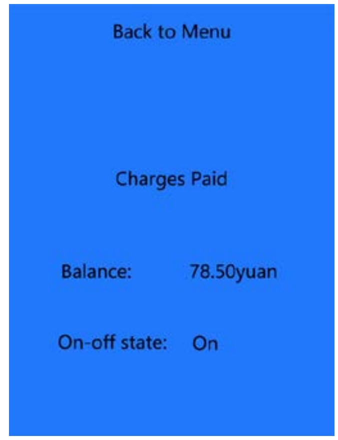

Fig. 15. Interface of successful consumption

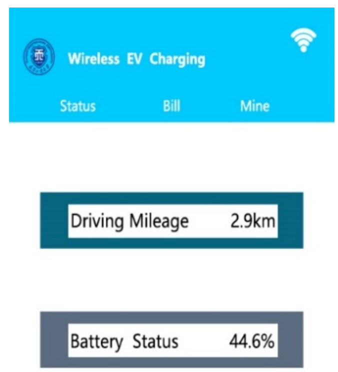

Fig. 16. APP Interface of mobile phone

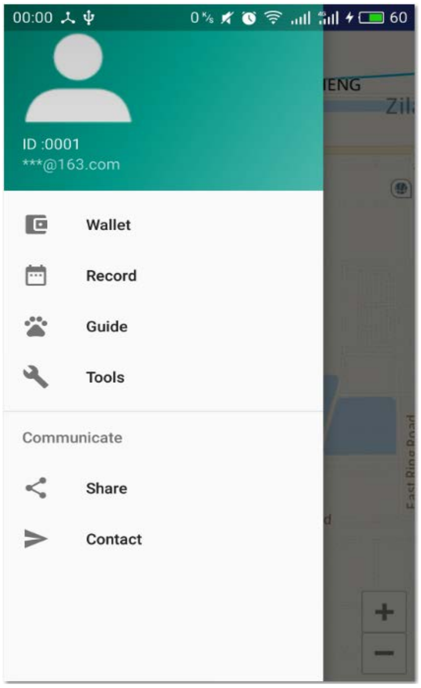

Fig. 17. User interface management

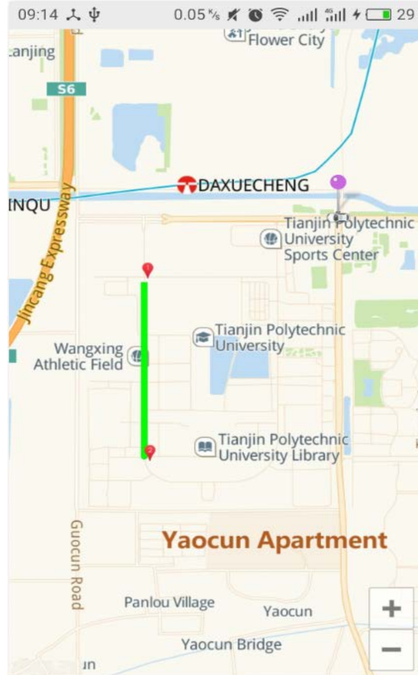

Fig. 18. The position of electric vehicles

C. User Interface Management

After login, user can perform corresponding operation, including wallet, record, guide, tools and online customer service. The interface is shown in figure 17.

The user can check the balance by wallet, the charging history by record, operating manual by guide, system settings by tools. Users can share the charging process in the network. If he has problems, he can contact customer service and get help.

D. Location and Road Display

Testing site takes Tianjin Polytechnic University campus as an example. User opens the phone client, the purple point is the current location of the EV, using the green line to label dedicated wireless charging road, as is shown in figure 18.

The wireless charging road is seen as a gas station, which can charge for EV while the EV driving.

E. Navigation

Among of all the charging roads, the driver chooses a suitable one first. After the selection, the interface shows the driving routine of the designated road, and helps the driver to enter the charging road. At the same time, the system shows multiple driving routes for drivers to choose, as is shown in figure 19.

F. Charging Expense

EV sends charging request after driving into the entrance of the road. When the network server receives the charging request, the road will start one or more charging coil. It is shown in figure 20.

Fig. 19. Path planning

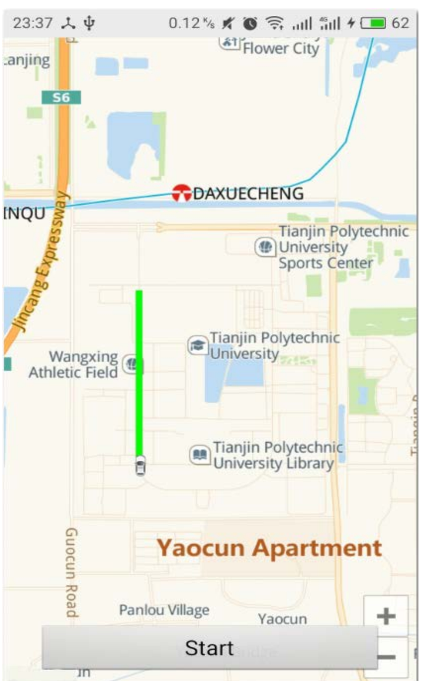

Fig. 20. Start charging

According to the position and speed of EV, the system turns on one or more transmitting coils. In consideration of the moving direction of the vehicle, the system will turn on the next charging coil and turn off the previous one. Drivers will send a stop charging request when charging is completed or they don't want to charge. It is shown in figure 21.

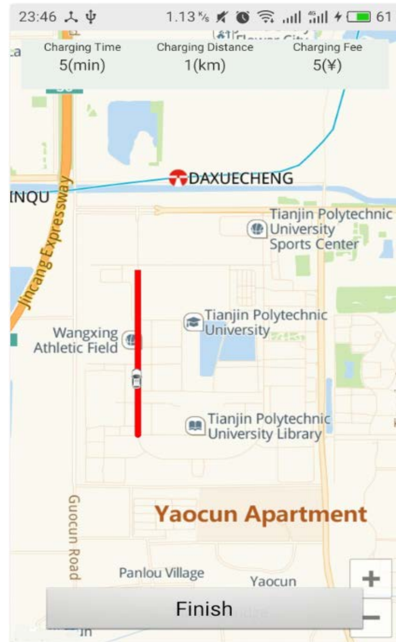

Fig. 21. Finish charging

The network server will send the bill to users after receiving the charging request. After settling bill, the charging ends. The experimental results are shown in figure 22.

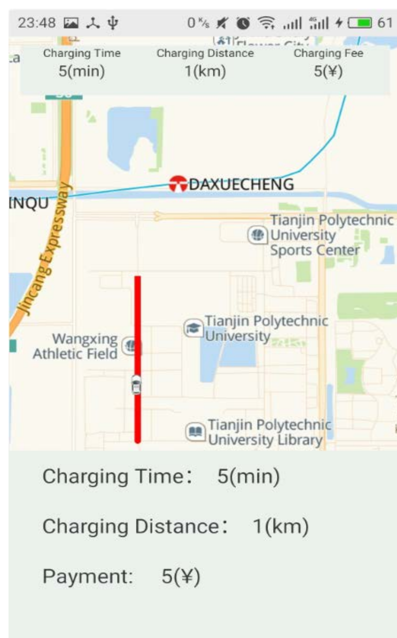

Fig. 22. The process of charging and billing

V. CONCLUSIONS

The paper has proposed a dynamic wireless charging system for electric vehicle. Finite-element analysis is performed using COMSOL to simulate the left-right deviation and different horizontal displacement of the coupling coils. STM32 microprocessor is utilized to realize the functions, including identity and verification, power statistics and billing function, information display and interaction. A service platform based on the IOV has been build, which achieves the functions, such as proposed location, charging road display, path planning, navigation, start or finish charging request, payment. The design improves the intelligence of the WPT system, which has guiding significance for large scale wireless charging of EV. In the future, we will further optimize the billing algorithm, develop a variety of billing methods, such as mileage, power and time billing to improve the satisfaction of drivers.

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