A study on modeling of wireless charging system based on fuzzy logic control

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Abstract. When the wireless charging system charges the lithium battery, in order to reduce the size of the receiver. With the increase of the charging power of the lithium battery, the charging strategy of the lithium battery should be changed accordingly, so as to improve the performance of the lithium battery. According to the characteristics of the wireless charging system and the charging strategy of the lithium battery, the whole system is dynamically adjusted based on the fuzzy logic control principle, so that the system can provide the required charging power for the lithium battery under different charging strategies. In this paper, the circuit model of the wireless charging system and the equivalent model of the lithium battery are established respectively, and the fuzzy logic control strategy is proposed. Finally, the accuracy of the control strategy is verified by simulation, which provides a reference for the dynamic adaptive adjustment of the wireless charging system.

1. Introduction
In 1891, when Nikola Tesla succeeded in transmitting electricity wirelessly to a target electrical appliance, the world entered the era of wireless power transfer (WPT). At present, wireless power transfer is widely used in life, because it makes the electrical appliances get rid of the shackles of wires, that is the reason why more people choose it. Wireless charging technology is developing toward miniaturization and lightweight. Reducing the volume of wireless power transmission devices will undoubtedly improve the convenience of use. Many scholars studying wireless charging technology pay more attention to the transmission efficiency and transmission power of the system. However, the research on the control strategy of lithium battery wireless charging is not a research hotspot. Since the rechargeable lithium battery is a complex nonlinear system, the parameter states reflected in the wireless charging process will change with the increase of charge. In order to simplify the receiver circuit of wireless charging system, a method to directly charge the battery after rectified from the receiver is proposed [1]. In this method, by controlling the DC voltage of the inverter input from the transmitter, the DC current and voltage of the receiver rectifier can directly meet the charging requirements of the lithium battery. In [2], the author presented a fuzzy logic control method for optimizing power transfer. The fuzzy logic controller was used to adjust excitation frequency and change capacitance by amplitude and phase of the input current of the primary side of the inductive link. The electric vehicle charging is a high-power work. As [3] shows, the output voltage which is charging voltage is maintained constant at the load side with the help of the proposed fuzzy logic
controller. When the battery equivalent resistance increased from 210 ohms to 230 ohms, the fuzzy logic strategy can always hold on 400V output. [4] is more progressive than [3]. The author proposed a new fuzzy logic control method which is united with the fuzzy control adaptability and robustness and the GA with optimization. This method presents smaller overshoot and fast transient response with less oscillation.

The PID control method has a history of nearly 70 years since its appearance. It has become one of the best control strategies for the dynamic system, because of its advantages such as simple principle, great stability, high working reliability and convenient regulation [5]. Usually, the electronic system can be controlled by PI which omitted derivative action. But in the absence of relevant empirical values and conditions, the PI parameters are difficult to determine. Therefore, this paper uses the fuzzy logic control method on PI to control the wireless charging system. In the Section II, the principle of wireless charging system is described. The equivalent circuit model and equation are obtained. In the Section III, the method of fuzzy logic control is determined. In the Section IV, the lithium battery equivalent model and the Simulink model of wireless charging system are established respectively. In the end, the simulation results are analyzed and summarized.

2. Wireless power transfer

2.1. The principle of wireless power transfer

The magnetic coupling wireless power transfer system consists of a transmitter, a receiver and a load. In the transmitting circuit, the high-frequency inverter is used to convert the DC power supply of the Input into the high-frequency AC source excitation which is consumed by the transmitting coil. Because of the high-frequency AC excitation, the transmitting coil will generate the high-frequency time-harmonic electromagnetic field. The magnetic coupling wireless transmission of electric power is realized in the near field area of the electromagnetic field. The receiver converts the power into a high-frequency AC source through the receiving coil in the near field. The DC current with the corresponding voltage value obtained through rectification and filtering, then used by the load. In order to improve the power transmission efficiency, the transmitting circuit and the receiving circuit can achieve resonance according to the series or parallel capacitance of the corresponding self-inductance value of the transmitting coil and the receiving coil respectively, which is also known as resonant wireless power transfer. As shown in the Figure 1, magnetically coupled wireless power transmission system.

![Figure 1. The wireless power transfer system of magnetic coupling.](image)

2.2. The equivalent circuit model of WPT

The transmitting circuit and receiving circuit in the wireless power transfer system have many forms of compensation, the common ones are series-series (S-S), series-parallel (S-P), parallel-series (P-S) and parallel-parallel (P-P), which are named after the position of the compensation capacitance relative to the coil in the circuit. The following Figure 2 shows the topology of the S-P compensation circuit.
For the load of lithium battery which is a voltage source, the receiver generally adopts the parallel form of compensation capacitance. Series - parallel (S-P) form has constant voltage output characteristics, and is not affected by load and coupling coefficient [6]. Therefore, the series-parallel (S-P) form, as shown in Figure 2, was selected in this paper to analyze the mutual inductance model according to the equivalent circuit. The load circuit is equivalent to an RLC element \( Z_L \).

In the figure, \( C_1 \) is the compensation capacitor of the transmitting side, \( R_1 \) is the equivalent resistance of the transmitting coil, \( C_2 \) is the compensation capacitance of the receiving side, \( R_2 \) is the equivalent resistance of the receiving coil, \( L_1 \) and \( L_2 \) are the self-induction of the transmitting coil and the receiving coil respectively. \( Z_L \) is the Load circuit and \( M \) is mutual inductance.

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\begin{align*}
U_1 & = (R_1 + j\omega L_1 + \frac{1}{j\omega C_1})I_1 + j\omega MI_2 \\
U_2 & = j\omega MI_1 + \frac{1}{\frac{1}{j\omega C_1} + \frac{R_2}{L_1} + j\omega L_2}I_2 \\
U_2 & = -Z_LI_2
\end{align*}
\] (1)

According to the equivalent circuit model of wireless charging system and equation, the basis for establishing the model can be obtained, which provides theoretical support for the following Simulink modeling.

3. Fuzzy logic control

3.1. The principle of fuzzy logic control

Based on the basic theory of fuzzy mathematics, the corresponding fuzzy logic control rules are established and then the fuzzy logic controller is established. Fuzzification is the process of translating input values into linguistic values to represent them and using linguistic variables to describe the measured physical quantity. The corresponding membership degree can be obtained according to the appropriate language value in order to complete the fuzzification. Combined with database and rule base, the fuzzy data is defined. The control objectives and methods are described [7]. The core of fuzzy controller lies in its logical judgment, it imitates human judgment rules to get inference, and then decides how to control it next. Finally, the inference obtained is transformed into the actual control signal as the input value of PI parameters. Therefore, the fuzzy logic PI control strategy can be realized.

According to the working principle and electronic circuit characteristics of wireless power transfer, the selection of fuzzy rules is affected. The Mamdani method is chose, because the system is a continuous dynamic circuit. It is also a nonlinear complex system with multi-input and single output, so Self-Tuning fuzzy logic is a good option [8]. Figure 3 shows the working process of a fuzzy logic feedback controller.
In Figure 3, $e$ is error value, $ec$ is rate value of error, $A$ is fuzzification of error, $B$ is fuzzification rate of error, $C$ is fuzzy control value, $u$ is output value. In this part, the output value is a regulating to the PI controller. The controller parameters which can be regulated are proportion coefficient and integral coefficient. The control strategy as Figure 4 shown, which integrate Self-Tuning fuzzy logic and PI controller together.

3.2. Fuzzy logic membership
The operating range should be determined. According to the charging voltage of wireless charging system, the error value $e$ and the rate value of error $ec$ are determined in the range of $[-1,1]$. The $k_p$ and $k_I$ are determined in the range of $[-0.3,0.3]$ and $[-0.03,0.03]$ respectively [9].

This paper sets seven classes, PB means ‘Positive Big’, PM is ‘Positive Middle’, PS is ‘Positive Small’, ZO is ‘Zero’, NS is ‘Negative Small’, NM is ‘Negative Middle’, NB is ‘Negative Big’. Among of them, the NB and PB classes are used the Z-type membership function, Because Z type can more manipulating flexible than Triangular type. As Figure 5 shown, the plot of fuzzy logical membership function.
3.3. Fuzzy logic rules

The fuzzy logic rules decide how much value will be changed on the PI parameters. The adjustment regulation is considered by analyzing wireless charging system model with the control performance of fuzzy membership functions. The fuzzy rules in this controller are summarized in Table 1.

| $e^i e_c$ | NB | NM | NS | Z | PS | PM | PB |
|-----------|----|----|----|---|----|----|----|
| NB        | PB | PB | PB | PM | PM | PB | PB |
| NB        | NB | NB | NM | NM | NS | Z  | Z  |
| PM        | PM | PM | PM | PS | PS | PS | PM |
| NB        | NB | NB | NM | NS | NS | Z  | Z  |
| NS        | PB | PB | PB | PM | PM | PM | PM |
| NS        | NB | NB | NM | NS | Z  | PS | PS |
| Z         | PS | PS | Z  | Z  | Z  | PS | PS |
| NM        | NM | NM | NS | NS | Z  | PS | PS |
| PS        | PM | PM | PM | PS | PS | PS | PS |
| PM        | PB | PB | PB | PM | PM | PM | PM |
| PB        | Z  | Z  | PS | PS | PM | PB | PB |

According to the wireless charging system character and equivalent circuit model, we should analyze to set the value of proportion coefficient. The $k_p$ is a parameter which is an important coefficient to improve sensitivity on the response of error value. The relationship with error value and rate value of error are determined, if the $k_p$ is too large will lead to overshoot larger. It will increase the number of oscillation and extend the time of convergence. In this principle, the relationship between the input and the $k_p$ parameter is determined, as shown in Figure 6.

**Figure 6.** The relationship between inputs and $k_p$ in wireless charging system.

The integral parameter of the PI is to prevent a stable error existing after proportion adjustment. If the stable error cannot eliminate, the system will keep this error and cannot be further changed unless the actuator executes the other case. In order to get an accurate control performance, if the integral coefficient value is too large, the integral supersaturation and overshoot will be happened. Stand in this point, the relationship between inputs and the $k_i$ parameter is built, as shown in Figure 7.

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4. Modeling of wireless charging system with fuzzy logic control

Before establishing the whole system model, the lithium battery as the load is in a dynamic state due to its parameters changing all the time during the charging process. In order to better control the whole dynamic system, it is necessary to establish an accurate equivalent model of lithium battery. The accuracy of the model directly determines the effect of model predictive control in practical application. Therefore, in view of the popular lithium battery equivalent model, this paper chooses the two stage RC equivalent model. The two stage RC model actually adds two sets of RC parallel circuits to the ideal internal resistance equivalent model. The equivalent circuit is shown in the Figure 8.

![Figure 8. The Equivalent circuit of two-stage RC model.](image)

**Figure 8.** The Equivalent circuit of two-stage RC model.

![Figure 9. The Equivalent model of two-stage RC in Simulink.](image)

**Figure 9.** The Equivalent model of two-stage RC in Simulink.
The model consists of an ideal voltage source $U_{OC}$, an internal resistance of the lithium battery $R_0$. $R_P$ is the polarization resistance, $C_p$ is the polarization capacitance, $R_s$ is the surface effect resistance, $C_s$ is the surface effect capacitance. The discharge equivalent model of lithium battery is established according to the discharge data of lithium battery obtained from existing experiments. The discharge equivalent model of lithium battery established in Simulink as Figure 9.

Based on the discharge equivalent model of lithium battery, the charging equivalent model is established and the whole wireless charging system model is obtained, as shown in Figure 10. The whole system consists of a front Buck circuit, a high-frequency inverter circuit, a wireless power transfer equivalent circuit, a rectifier circuit and a lithium battery. The dynamic stability of the whole circuit is realized by adjusting the voltage of the front Buck circuit and the switching frequency of the high-frequency inverter. In the control part, the fuzzy logic controller realizes the intelligent adjustment of PI by controlling $k_P$ and $k_I$.

![Figure 10. The wireless charging system model in Simulink.](image)

5. Result of simulation

There are many charging methods for lithium batteries. This paper simulates the variable voltage intermittent charging method. Variable voltage intermittent charging method is different from variable current intermittent charging method in that the first stage is not intermittent constant current but constant voltage. This method is more consistent with the optimal charging curve. At each constant voltage charging stage, the charging current decreases exponentially, which is in line with the characteristic that the battery current gradually decreases with the charging process. As shown in Figure 11, variation curve of wireless charging voltage is controlled by the fuzzy logic PI with the charging time.

![Figure 11. The charging voltage curve controlled by fuzzy logic PI.](image)
From the change curve of charging voltage, it can be seen that the wireless charging system will adjust the next charging voltage according to the feedback of the charging state of the lithium battery under the control of fuzzy logic, so as to realize the adaptive variable voltage charging strategy. The response time less than 0.02 seconds when the charging voltage change. Fuzzy logic control has a better performance than increment PI control which response time is 0.06 sec. Compared with increment PI control, the characteristics are robustness and adaptivity when charging for different batteries with different strategies.

6. Conclusions
From the modeling and simulation of the wireless charging system and lithium battery, the fuzzy logic control strategy can achieve a perfect control performance, especially in the variable voltage charging strategy which can realize adaptive control. The simulation result obtains that the fuzzy logic control response time shorter than increment PI control 0.04 sec. The wireless charging strategy based on fuzzy logic control principle can better track the charging state of lithium battery and make the whole system realize dynamic stability. The work in this paper can provide a reference for the control strategy and prediction model which are accurate and robust on the output of the wireless charging system.

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