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Wireless Charging Efficiency Optimization Method Based on Adaptive Robust Control

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Abstract:

This paper designs, analyzes and optimizes the electric vehicle wireless charging system and its control method. Compared with the traditional plug-in conduction charging, wireless charging is more convenient, safe, reliable and has better environmental adaptability. Inductive power transmission technology (IPT) is the main technology for wireless charging of electric vehicles and plug-in hybrid vehicles. Based on the fundamental approximation method, the critical self inductance of the primary or secondary coil is derived in this paper. This critical value reflects the power transmission capacity and control performance of the two chargers when they are interoperable. Compared with the non integrated structure, the magnetically integrated LCC compensated wireless charging system can transmit the same power with smaller compensation inductance. Based on the voltage dependent dynamic state space model, four working modes of magnetically integrated LCC compensated wireless charging system are studied in this paper. Simulation and experimental results show that the voltage dependent equivalent circuit model can be effectively applied to the basic characteristic analysis of wireless charging system. The voltage dependent dynamic state space model is more accurate and realistic. In addition to reflecting the basic characteristics of the wireless charging system, it can also reflect the working mode of the wireless charging system.

***Keywords**: Adaptive Robust Control, Wireless Charging, Efficiency Optimization, Inductive Power Transmission Technology.*

I. INTRODUCTION

At this stage, the advantages of electric vehicles are obvious, but there are also many factors, such as maximum speed and mileage, which restrict the further development of electric vehicles [1-2]. The power of electric vehicle comes from power battery, which needs periodic charging, which is one of the limiting factors for the development of electric vehicle. At present, the main application of the two charging methods of electric vehicles is the contact

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charging of charging pile, but the contact charging has many disadvantages and deficiencies compared with the non-contact charging [3]. Resonant non-contact charging completes the wireless transmission of energy through magnetic resonance coupling. It does not need direct electrical connection, and can be controlled intelligently and automatically [4]. It does not need manual operation, and can effectively avoid electric shock [5-6]. There are many advantages of non-contact resonant coupling charging for electric vehicles, and it has a good application prospect. Contact charging has the trend of being replaced by non-contact resonant coupling charging [7].

The application of magnetic coupling resonance non-contact energy transmission technology for wireless charging of electric vehicles can promote the further development of electric vehicle industry, and the state also has great support for this charging method in policy and capital. Therefore, this charging method will soon be widely recognized and applied in China [8-9].

II. RESEARCH ON PRINCIPLE AND CONTROL STRATEGY OF RESONANT RADIO ENERGY TRANSMISSION

1.Theoretical research on resonant circuit

Resonance system is widely used in life, which can be divided into RLC series resonance and RLC parallel resonance. R is the internal resistance of resonance inductance L and resonance capacitance C. in fact, in high-frequency use, the internal resistance of resonance capacitance C is very small, while the internal resistance R_L on resonance inductance is large, so the influence of its internal resistance on resonance system needs to be considered. In the analysis, the influence of the internal resistance R_C of the resonant capacitor is ignored for simplicity.

Impedance in resonant circuit [10-13]:

$$Z_S = R_L + j\omega L + \frac{1}{j\omega C} \quad (1)$$

KVL equation of resonant circuit:

$$\dot{U}_S = \left[R_L + j\omega L + \frac{1}{j\omega C} \right] \dot{I}_S \quad (2)$$

When the terminal voltage Us is in phase with the current Is, resonance occurs, that is:

$$\omega L - \frac{1}{\omega C} = 0 \quad (3)$$

The resonant angular frequency $\omega_s = \frac{1}{\sqrt{LC}}$, the minimum impedance Z = R_L, the energy of the resonant inductance and the resonant capacitor in the circuit is the same, the direction is opposite, and offset each other. One of the parameters of resonant inductance, the quality factor

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is the ratio of impedance. Quality factor Q:

$$Q=\frac{\omega_s L}{R_L}=\frac{1}{\omega_s C R_L}=\frac{1}{R_L}\sqrt{\frac{L}{C}} \quad (4)$$

In series resonator, the effective value of resonant inductance voltage and resonant capacitor voltage is equal:

$$U_L=U_C=QU_S \quad (5)$$

In the series resonant network, the voltage on the inductor and capacitor is very high, which has a great voltage stress on the device. Series resonance is constant voltage, so it is also called "voltage resonance". When the terminal power supply is a constant voltage source, the resonant network mostly adopts series resonant structure.

2.Research on control strategy

The non-contact closed-loop charging of the battery is carried out through the radio energy transmission technology. The charging of the battery is divided into different stages. The initial stage is to set the upper voltage limit and charge the battery with a constant current. When the primary side and secondary side of loosely coupled transformer are asymmetric, in order to meet the design requirements of system output power and system efficiency, it is necessary to introduce control strategy into the system to realize the closed-loop stable operation of the system. When the horizontal displacement and vertical distance of the system change, the system can be adjusted to meet the design requirements in a short time for stable operation.

Nowadays, the frequency conversion closed-loop control methods commonly used in wireless charging system mainly include phase-locked loop control technology and PI control technology. Phase locked loop control of wireless charging system is to detect the phase difference of voltage and current on the secondary side, and change the working frequency point of the system through the phase difference. It is necessary to collect the phase of high-frequency and high-power voltage and current, which has high requirements for hardware design. PI closed-loop control is widely used in industry. PI control technology of wireless charging system is to detect the charging current of the battery and calculate the deviation between the charging current and the set value to control the working frequency of the system and realize constant current control. Battery charging is a constant current control, so the digital PI control mode is selected for the wireless charging system of electric vehicle to realize the frequency conversion closed-loop control of the system.

The system takes the charging current of the battery as feedback information to control the working frequency of the system. The secondary controller completes the collection, conditioning and digital filtering of battery charging current. Use wireless communication ZigBee technology to send to the original side. In the primary side, the frequency of PWM signal is changed through PI control, that is, the working frequency of the system is changed to realize the control of the system.

The system adopts incremental PI control. Incremental PI control algorithm:

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$$\Delta u(k) = K_p\left(e(k) - e(k-1)\right) + K_i e(k) \quad (6)$$

Because the output of increment control is the adjustment increment, the value is small, and the action caused by adjustment error is small. The incremental type only needs the error between the current value and the last time, with small storage, no accumulation and small calculation. The integral weakening control, integral separation control and dead time control algorithms are introduced. The integral weakening control is to weaken the integral when the regulated object exceeds the maximum or minimum limit to prevent the regulated object from exceeding the limit for a long time. Integral separation control algorithm:

$$K_i = \beta K$$
$$\beta = \begin{cases} 1 & \text{Normal algorithm} \\ 0 & \text{Integral separation} \end{cases} \quad (7)$$

The integral separation control can automatically adjust and switch between P control and PI control. Dead band control algorithm:

$$e(k) = \begin{cases} < deadzone & \text{No adjustment} \\ > deadzone & \text{PI regulation} \end{cases} \quad (8)$$

It can avoid unnecessary oscillation caused by frequent regulation. The algorithm is simple. Only one dead zone parameter needs to be added to control whether PI regulation is carried out. The introduction of the above three improved PI control algorithms can better make the system achieve the set output.

III. DESIGN OF WIRELESS CHARGING SYSTEM FOR ELECTRIC VEHICLE

The system uses the principle of resonant electromagnetic coupling to charge the power battery of electric vehicle through non-contact magnetic coupling coil. Firstly, the power frequency two-phase current is rectified to output DC with controllable voltage, and the DC is transformed into high-frequency AC through full bridge inverter. Then the AC is applied to the primary resonant coil, and the secondary coil is coupled to the energy through the magnetic field to rectify the AC on the secondary side and charge the battery. The closed-loop control of the system is carried out, and the PI control strategy is used to adjust the working frequency of the system to make the system work stably.

The system is divided into two parts: energy flow and information flow. Energy flow refers to the electric energy transmitted from the primary side to the secondary side through a non-contact transformer. After high-frequency rectification, the electric vehicle power battery is charged. It is composed of high-frequency full bridge inverter circuit, LC resonant network and high-frequency rectifier bridge. Information flow refers to the non-contact communication between the primary side and the secondary side. The communication unit is controlled by its main control unit to realize the information flow of the primary and secondary sides, and the PI

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control strategy is used to realize the closed-loop control of the whole system.

1.Hardware circuit design

In a single inverter circuit, large pulse spikes will be generated at the moment when the switch is turned on and off, that is, surge voltage. These pulse spikes are likely to damage the MOSFET switch because the instantaneous voltage is too high. Therefore, the buffer absorption effect of pulse spikes directly affects the parameter performance and working life of the switch. RCD absorption circuit is mostly used in absorption circuit, and there are mainly charge discharge RCD absorption circuit and discharge suppression RCD absorption circuit.

Both absorption circuits can effectively suppress instantaneous pulse surge voltage and are widely used in inverters. The discharge suppression absorption circuit first stores the pulse surge voltage in the capacitor and acts on the bus through the resistance, which affects the bus voltage and then the inverter output waveform. The buffer absorption resistance of the system adopts high-power resistance. Moreover, due to the existence of buffer diode, the resistance value of the absorption resistance of charge discharge RCD absorption circuit can become larger. It can solve the stress problem of MOSFET switch when it is turned on. The absorption circuit of the inverter circuit of the system adopts charge discharge RCD absorption circuit.

There are also certain requirements for the selection of absorption resistance. Ensure that the power on the absorption capacitor is released through the absorption resistance within the on time of the switch. The following requirements shall be met:

$$3RC < \frac{T_{con}}{2} \quad (9)$$

Where R is the absorption resistance value, C is the absorption capacitance value, and Tcon is the conduction time of the switch tube.

At the moment when the switch is on, ensure that the current flowing through the absorption resistance is not too large to prevent damage to the switching device. Need to meet:

$$\frac{U_0}{R} < I_D \quad (10)$$

Where U_0 is the DC bus voltage and I_D is the drain circuit of the switch tube. The selection of absorption resistance shall ensure that the above two necessary conditions are met. The absorption resistance of the absorption circuit in the system is determined as 50Ω and the absorption capacitance is determined as 1nF.

2.System software design

The main controller of the primary side is STM32F103. Keil4 is selected as the programming environment and C language is used for programming. The main program first initializes the functions used by the main controller. The clock must be initialized first. If the clock of the corresponding function is not initialized, the function will not work. The initialization of GPIO includes setting the signal direction and working mode of the pin, and setting its maximum output rate for the output pin. All pins used must be initialized.

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The ad module of STM32F103 is a 12 bit successive approximation ad, with 18 ad channels and a variety of working modes and storage modes. It should be set one by one during ADC initialization. The ad on the primary side is set to be started by software control to control the opening of AD sampling. During initialization, reset and clear the AD sampling data memory to prevent affecting the operation of the program. Set the interrupt type of the two ADCs as the analog watchdog type in the program. When the collected value exceeds the preset high or low threshold, the watchdog interrupt will be generated, and then jump to run the interrupt program.

Set the two keys as external interrupt to manually control the frequency of PWM signal to realize manual control and adjustment of the working frequency of the system. In the program, there are ADC watchdog interrupt, braking interrupt of advanced timer, timing interrupt of ordinary timer and serial port receiving interrupt. For different interrupts, the interrupt level shall be set during initialization to make the priority of different interrupts different, so as to prevent the confusion of program execution caused by the inability to judge the priority when an interrupt occurs.

The system adopts PI control strategy to realize closed-loop control and incremental PI control. The frequency increment of the system is obtained by executing PI algorithm on the secondary side current value. Two improved algorithms, limit weakening and integral separation, are introduced. When the frequency is greater than the set maximum value or less than the set minimum value and enters the non set range, the weakening integral algorithm is executed to change the integral adjustment parameters. When the deviation between the collected value and the set value of current is greater than the preset maximum deviation value, integral separation shall be carried out to reduce the adjustment time. Return the working frequency value and store this deviation as the previous deviation for the next adjustment. The previous deviation is considered to be 0 during the first adjustment.

The types of working faults are distinguished in the program, and different faults are handled accordingly in the fault handling program. In the program, first judge the fault type, and then respond.

IV. EXPERIMENTAL STUDY ON SYSTEM CHARACTERISTICS

The load of the system is the power battery, and the medium distance Senlai nickel hydrogen battery is selected to be applied to FAW and Chang'an electric vehicles. The battery is composed of 240 Ni MH batteries, and the upper limit of total voltage is 360V. It can achieve more than 100000 cycle charging.

In the process of charging the battery through wireless charging technology, it is necessary to conduct high-frequency rectification and high-frequency filtering on the waveform output by the secondary side of the resonant network through the high-frequency rectifier bridge to turn it into a DC with small ripple, and then charge the battery. In the process of bus voltage rising, the

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secondary side resonant voltage begins to be a resonant sinusoidal waveform. When the secondary side voltage rises to a certain value, its waveform changes from sinusoidal waveform to square waveform.

When the electric vehicle is charged wirelessly, due to the driver's manual manipulation of the electric vehicle, there are different horizontal displacements on the primary and secondary sides of the loosely coupled transformer, which makes the primary and secondary sides of the transformer not completely symmetrical and affects the transmission performance of the system. However, the asymmetry can not be completely eliminated, so it is necessary to study the influence degree and trend of system transmission performance when horizontal sideshift. The inductance of the resonant coil is actually measured, and then the coupling coefficient of the system can be obtained indirectly through calculation, as shown in Table 1. When the horizontal sideshift distance changes, the influence on the system coupling coefficient can be obtained. When the sideshift, the coupling coefficient decreases monotonically. When the sideshift distance is within 8cm, the change of the coupling coefficient is very small and has little influence on the transmission of the system. When the lateral displacement distance is greater than 8 cm, the coupling coefficient changes greatly and decreases rapidly with the increase of lateral displacement distance.

TABLE I. Influence of horizontal sideshift distance on system coupling coefficient

HORIZONTAL SIDESHIFT / CM	COUPLING COEFFICIENT	CHANGE VALUE	CHANGE RATE%
0	0.1853	-	-
2	0.1853	0.0000	0.0000
4	0.1839	0.0014	0.7428
6	0.179	0.0049	2.7316
8	0.1727	0.0063	3.6484
10	0.164	0.0087	5.2909
12	0.1537	0.0103	6.7023
14	0.1437	0.0100	6.9811
16	0.1336	0.0100	7.5178

The influence of horizontal sideshift distance on the output power and overall efficiency of the system is analyzed through experiments. The influence of input voltage and sideshift distance on the output power of the system. The bus voltage of the inverter circuit is boosted from 190V to 300V, and the sideshift distance changes in the range of - 15cm-15cm. The output power increases monotonically with the increase of bus voltage. When the sideshift distance is less than 8 cm, the sideshift distance has little effect on the system output power. This is due to the directional effect of the ferrite core on the magnetic field. When the sideshift distance is beyond 8cm, the output power of the system decreases with the increase of the sideshift distance. When the sideshift distance is large, the bus threshold voltage at which the system starts charging increases. It is consistent with the change trend of coupling coefficient.

V. CONCLUSION

This paper studies the magnetic resonance wireless energy transmission, which takes the battery of electric vehicle as the load to realize the non-contact charging of the battery. The transmission mechanism of the system is studied theoretically and analyzed by modeling and simulation, which provides guiding principles for the design of the system, and completes the design of system hardware and closed-loop software.

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