Inductively Coupled WPT Circuit Design for Power Battery Charging in New Energy Vehicles

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Abstract. With the development needs of the new era, electric vehicles have become the preferred means of transportation with their environmentally friendly superiority and are moving towards an intelligent, wireless and grid-based future. However, the wired charging mode of electric vehicles does not meet this requirement and has many drawbacks, such as poor port adaptability, long charging time, and large land and labor costs. The wireless charging mode is naturally free of these problems and has been put into use in micro fields such as cell phone charging and watch charging. How to realize the utilization of wireless power transmission in the field of electric vehicles as soon as possible to realize charging while walking. In this paper, I will illustrate the advantages of Inductively Magnetically Coupled - Wireless Power Transmission (MCR - WPT), construct an optimized MCR - WPT circuit model to realize the wireless charging of battery, and give parameters such as energy utilization through Simulink simulation for theoretical justification. The results show that the MCR - WPT circuit can better realize the wireless charging of batteries with high safety and stability, and the MCR - WPT technology can play its advantages in the future large-scale wireless charging applications.

Keywords: Battery; wireless charging; MCR - WPT; Simulink simulation; energy utilization.

1. Introduction

Since the 21st century, the greenhouse problem has become a common global problem, and how to promote the application of new energy and clean energy, so as to achieve energy saving and emission reduction, has become the top priority regarding the country's livelihood. New energy vehicles stand out for their low-carbon and environmentally friendly features. After the government's "Four Five-Year Plan", China's electric vehicle sales and research progress are far ahead of the rest of the world [1].

Because of the special characteristics of the energy source of electric vehicles, the power battery has high requirements in terms of safety, operating frequency, operating voltage, service life, and cost. The existing wired charging of electric vehicles has problems such as long-time cost, line wear and tear risk, mileage limitation, etc., while WPT wireless current transmission technology, due to its advantages of long transmission distance, high power, and stability, makes the WPT circuit model suitable for wireless battery charging technology [2]. This paper takes inductively coupled WPT circuits as the research object to explain its model advantages, basic principles, and circuit model optimization to achieve the purpose of wireless energy transmission.

2. Power Battery Wireless Charging Advantage Analysis

The widespread use of these batteries has been hampered by safety issues, particularly related to explosions during high-temperature operation; affordability issues related to the cost of batteries for electric vehicles; and functional efficiency challenges related to charging/recharging and discharging times.

2.1. Temperature environment of power battery

Power battery can be mainly divided into electric core, module, battery pack, if the working temperature exceeds the threshold, it may lead to short circuit, breakage and other problems. Under the influence of high temperature for a period of time, the working performance of the power battery will be affected by a large negative impact, and it will more directly affect the service life of the battery and accelerate the aging speed of the battery [3]. Generally speaking, when the battery is at an operating temperature of 10 to 30 degrees Celsius, the chemical ions in the electrolyte diffuse at a higher rate, the electrical conductivity is stronger, and the battery capacity is enhanced [4]. The performance of lithium-ion batteries is greatly influenced by a number of important factors. These characteristics include the surface area of the different electrode materials, the conductivity of the electrodes and electrolyte, the diffusivity of lithium in the active electrode material, and the reaction rate constants of the electrode active sites [5].

Besides, the ambient temperature has a significant impact on lithium-ion battery performance, and the batteries can only operate safely and effectively within a very small temperature range. Lithium-ion batteries will have a rapid increase in internal resistance, a large reduction in charge and discharge capacity, and a significant reduction in the number of charge and discharge cycles at low temperatures. In addition to posing a risk to safety, excessively rapid battery charging and draining can also result in internal short circuits. If the battery temperature is not adequately regulated in a high-temperature environment, the high temperature will cause the diaphragm to melt, which will start a chain reaction of internal chemical reactions and produce a lot of exhaust gas. It will also cause the internal SEI membrane and the positive and negative active materials to decompose sequentially [6]. For example, if the temperature is in a suitable range, it can improve the vehicle mileage. Typically, a thermal management system is installed in the tram, which is activated when the temperature exceeds a certain value or falls below a certain value, and the adjustment of the temperature is realized by means of a fan and other measures. It is difficult to guarantee a favorable temperature range for the battery charging temperature in the traditionally applied wired charging pile without a humidifying device, while the MCR -WPT circuit reduces the heat loss, the temperature does not increase significantly, due to the superiority of the wireless transmission, with a high efficiency, and it is possible to reduce the complexity and dependence of the thermal management system in the case of using MCR -WPT charging circuits, reduced capacity frees up more circuit space.

2.2. EMI environment of power battery.

Most of the circuits in electric vehicles contain inverters with semiconductor-type components, which are susceptible to EMI through parasitic parameters (e.g., rate of change of current and voltage) at the moment of rapid shutdown, which can easily affect the overall battery compatibility efficiency of the trolley and the efficiency of the batteries, interferes with or even damages critical components such as batteries, drive motors, and low-voltage systems in electric vehicles and nearby vehicles [7]. EMI is a major challenge in the design of high-power drive systems. Previous studies have investigated the effects of EMI from inverters on motors and low-voltage components. However, less research has been done on the effects of EMI on batteries in electric vehicles. The CM and DM currents generated by the inverter flow into the battery through the AC cables, DC cables, and chassis, affecting the performance of the battery in terms of voltage, current SOC, heat generation, and lifetime. This paper focuses on the effects of conducted electromagnetic interference (EMI) generated by AC motor power inverters on Li-ion batteries in electric vehicles through CM and DM currents. [8]In order to protect Li-ion batteries, filters need to be added to reduce the CM and DM currents，one of the major advantages of the MCR - WPT circuit is the shielding from electromagnetic interference, which provides for the preservation of battery life during battery charging.

3. Inductively Magnetically Coupled WPT(MCR - WPT) model construction

3.1. MCR - WPT technology

Wireless Power Transmission (WPT) technology, known for its safety and stability, is widely used in electrical equipment and offers a high degree of operational freedom. WPT techniques are classified based on their proximity to the electromagnetic field source into two main categories: near-field coupling and far-field radiation. Near-field coupling includes methods like Magnetic Inductive Coupling (MIC) WPT, Magnetic Coupling Resonance (MCR) WPT, and Electric Coupling (EC) WPT, while far-field radiation encompasses technologies such as microwave WPT, laser WPT, and ultrasonic WPT. Among these, MCR-WPT stands out as a highly promising near-field technology due to its advantages in transmitting high power over longer distances with greater efficiency.

However, loose coupling in WPT systems can lead to decreased transmission efficiency and increased magnetic leakage, posing significant safety risks. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has established electromagnetic safety standards to address these concerns in WPT systems. Electromagnetic compatibility has become a key focus area in WPT technology development. Traditional electromagnetic shielding methods, such as integrating ferromagnetic cores like ferrite, are effective but are limited by their large size, which restricts coupling mechanism design. An alternative approach involves using non-ferromagnetic metals for shielding, but this can result in significant eddy current losses and overheating, particularly at higher power levels, compromising system safety [9].

MCR-WPT operates on the principle of magnetic resonance, utilizing a magnetic field to facilitate wireless power transfer between resonating coils in the transmitter and receiver. This technology extends the transmission range to a medium distance (centimeters to meters), overcoming the limitations of short-range methods like EC-WPT and MIC-WPT. Additionally, MCR-WPT offers higher efficiency and power compared to EC-WPT and is more efficient and powerful than far-field radiation technologies. Furthermore, MCR-WPT has broader applications, is easier to implement, and is cost-effective, as it is not affected by non-metallic, non-ferromagnetic obstacles. The circuit model of MCR-WPT includes components like a DC power supply, high-frequency inverter, transformer, and rectifier. Key parameters of the system include DC-AC-DC efficiency, energy utilization efficiency, resonance efficiency, and factors like the inductance and compensation of the circuit, as well as the wear and tear on the high-frequency inverter and rectifier. These advantages make MCR-WPT the most practical and promising WPT technology available [10]. The MCR - WPT Basic Model is shown in Fig. 1.

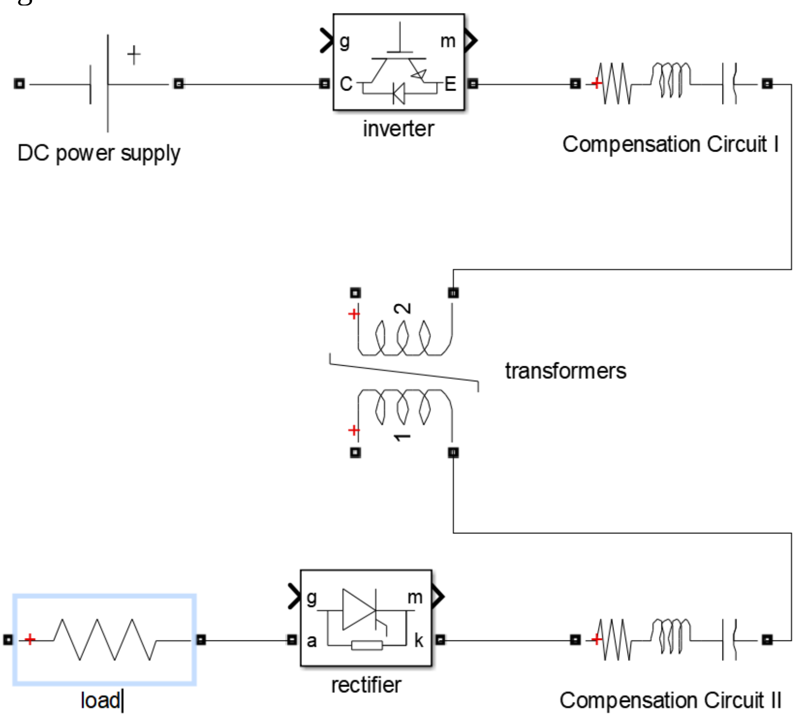

Fig. 1 MCR - WPT Basic Model

3.2. Equivalent Circuit Theory

A new magnetic component, referred to as magnetic induction intensity (or magnetic susceptibility), has transformed traditional scalar magnetic circuit theory into vector magnetic circuit theory. This evolution prompts the need for further exploration into how vector magnetic circuit theory aligns with existing electromagnetic theory. By employing principles from electromagnetic field theory, vector magnetic circuit theory, and conventional circuit theory, the magnetoresistance and magnetic inductance parameters within magnetic circuits are determined. The compatibility between these theories is then scrutinized, with an analysis focusing on how magnetic circuit parameters fluctuate with changes in magnetic circuit frequency. The findings are presented in the form of plotted graphs based on the general expressions derived for these parameters. Finally, the accuracy of these generic expressions is validated through Epstein frame measurements in conjunction with the magneto-electric power law, confirming the characteristics of the magnetic circuit [11].

At present, the main ways to study the MCR - WPT system model are equivalent circuit theory, coupled mode theory, two-port network theory, band-pass filter theory, etc. In this paper, we mainly use the equivalent circuit theory [12].

Based on Kirchhoff's voltage-current law and mutual inductance theory circuits can be basically equivalent to four models: series-series (S-S), series-parallel (S-P), parallel-series (P-S), and parallel-parallel (P-P). This is shown in Fig. 2.

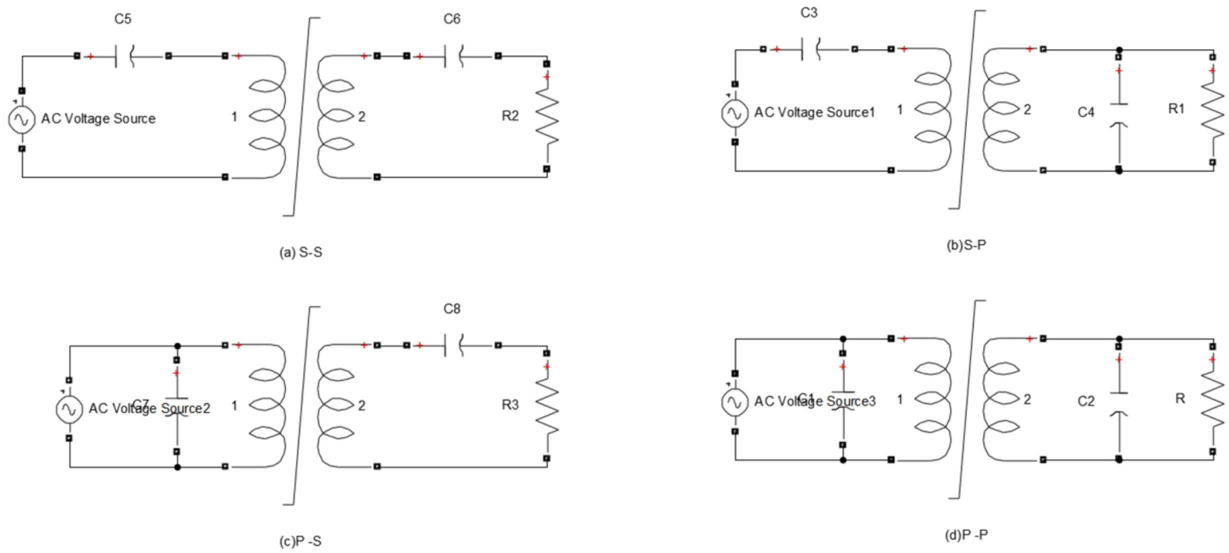

Fig. 2 Four MCR - WPT circuit structures

Establishing a dynamic wireless charging system model for electric vehicles and analyzing its output characteristics are the theoretical basis for improving the system performance and promoting the dynamic wireless charging technology.

charging technology. At present, the modeling methods for the dynamic wireless charging system of electric vehicles mainly include fundamental wave approximation analysis method and small signal analysis method. In order to simplify the model, the equivalent resistance is ignored, and the voltage and current are approximated to have only fundamental wave components, and the input impedance can be found through the mutual inductance theory, as shown in Table. 1.

Table. 1 Compensation capacitance values under resonance conditions [10]

Circuit Type	Transmitter Capacitance Value	Receiver Capacitance Value
S-S	$C_1 = \frac{1}{\omega^2 L_1}$	-
S-P	$C_1 = \frac{L_2}{\omega^2 L_1 L_2 - \omega^2 M^2}$	$C_2 = \frac{1}{\omega^2 L_2}$
P-S	$C_1 = \frac{L_1 R^2}{\omega^4 M^4 + \omega^2 L_1{}^2 R^2}$	-
P-P	$C_1 = \frac{L_2{}^2 L_1 - M^2 L_1}{M^4 R^2 + \omega^2 L_1 L_2{}^2 - \omega^2 M^2 L_2}$	-

R is the equivalent resistance, L1 and L2 are the self-inductance coefficients of the transmitting end and the receiving end, C1 and C2 are the compensating capacitances of the transmitting end and the receiving end, respectively, ω is the power frequency, and M is the mutual inductance coefficient.

Through Table. 1 can be obtained S-S type of compensation capacitance is the simplest, only with the self-inductance, frequency, while the other three models of compensation capacitance is too complex, in the actual situation of too many factors to consider, based on the S-S type of power supply model can be established as shown in Fig. 3 circuit model.

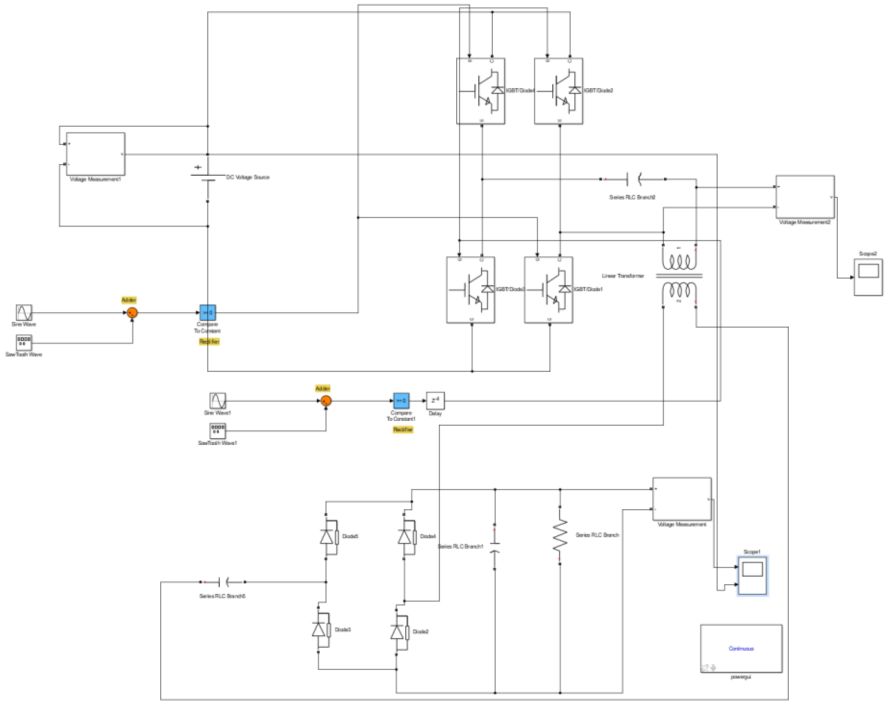

Fig. 3 MCR - WPT Circuit Modeling

3.3. Parameters affecting energy utilization

The S-S circuit model is simplified as shown in Fig. 4.

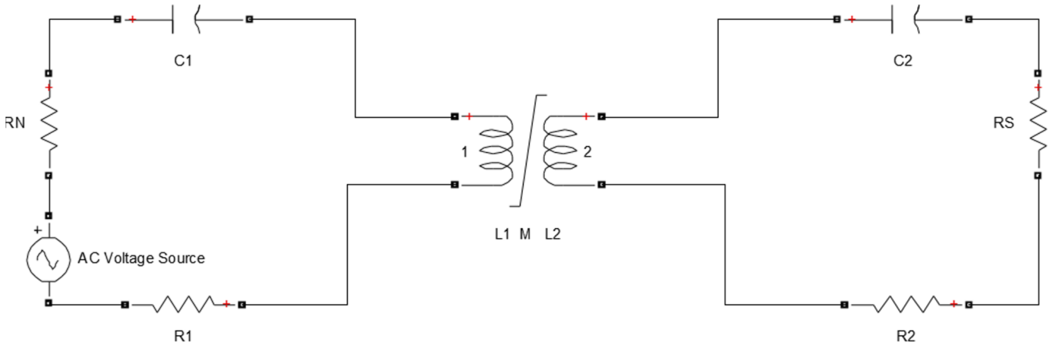

Fig. 4 S-S circuit model

It is obtained by Fourier analysis:

$$U_s = \frac{4U_1}{\pi}\left(\sin\omega t + \frac{1}{3}\sin 3\omega t + \frac{1}{5}\sin 5\omega t + ...\right) \tag{1}$$

US is the power supply at the transmitting end (AC power obtained by inverting the DC power supply), U1 is the DC power supply, ω is the inverter driving frequency, t is the time, M is the mutual inductance coefficient, I1 is the circuit at the transmitting end, and I2 is the current at the receiving end. Considering only the fundamental component, the rms value of the voltage U2 is obtained

$$U_2 = \frac{2\sqrt{2}U_1}{\pi} \tag{2}$$

By Kirchhoff's law and mutual inductance theory combined can be obtained

$$\begin{aligned} &U_2 = R_1 I_1 - j\omega M I_2 \\ &0 = -(R_2 + R_L) I_2 + j\omega M I_1 \\ &P_0 = U_2 I_1, P_u = I_2^2 R_L \\ &\eta = \frac{P_0}{P_u} = \frac{\omega^2 R_L}{\omega^2 (R_2 + R_L) + \dfrac{R_1 (R_2 + R_L)^2}{M^2}} \end{aligned} \tag{3}$$

It can be inferred that mutual inductance coefficient, operating frequency, equivalent resistance will affect the energy utilization.

4. Simulink-based circuit simulation analysis

The manufacturing process and real-world operating conditions can influence the performance of electronic components in magnetic resonance wireless power transmission systems. These factors often lead to random discrepancies between actual component parameters and their nominal values. Even minor variations in the parameters of electronic components within a magnetically coupled transmission system can result in significant fluctuations in the system's output characteristics. In this study, Simulink software is employed to simulate and analyze the circuit behavior. By carefully selecting electrical components with appropriate tolerances and adjusting the switching frequency in the series-series (S-S) configuration, the stability and reliability of the system's output can be significantly improved.

4.1. Modulated signal generation

A PWM triangular signal is generated by superimposing a triangular wave and a sinusoidal wave to provide a trigger pulse for the IGBT. The PWM square wave model is formed by superposition of sine and triangle waves as shown in Fig. 5

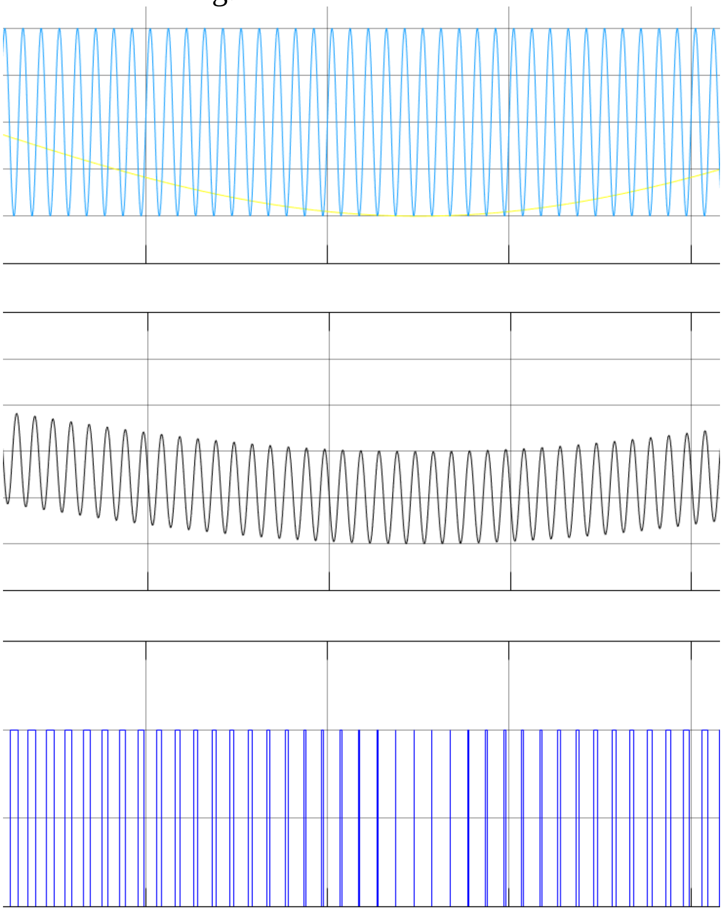

Fig. 5 Modulated PWM signal

The high-frequency inverter modulates it into a square wave signal as shown in Fig. 6. It can be found that the waveform in the figure is not a standard square wave signal, this is because the modulation of the PWM signal is not perfectly adapted to the IGBT, and there is an error in the trigger frequency, but it does not affect the experimental conclusions.

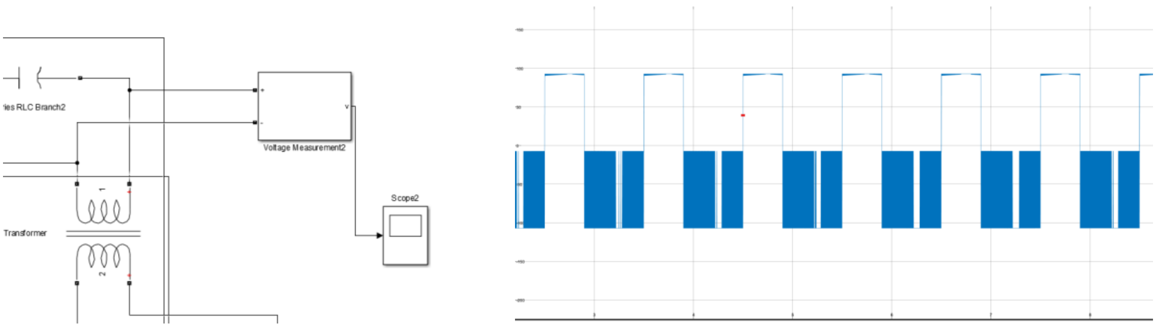

Fig. 6 High-frequency inverter modulates it into a square wave signal

Finally the DC-AC-DC transformation is successfully realized by rectification as shown in Fig. 7.

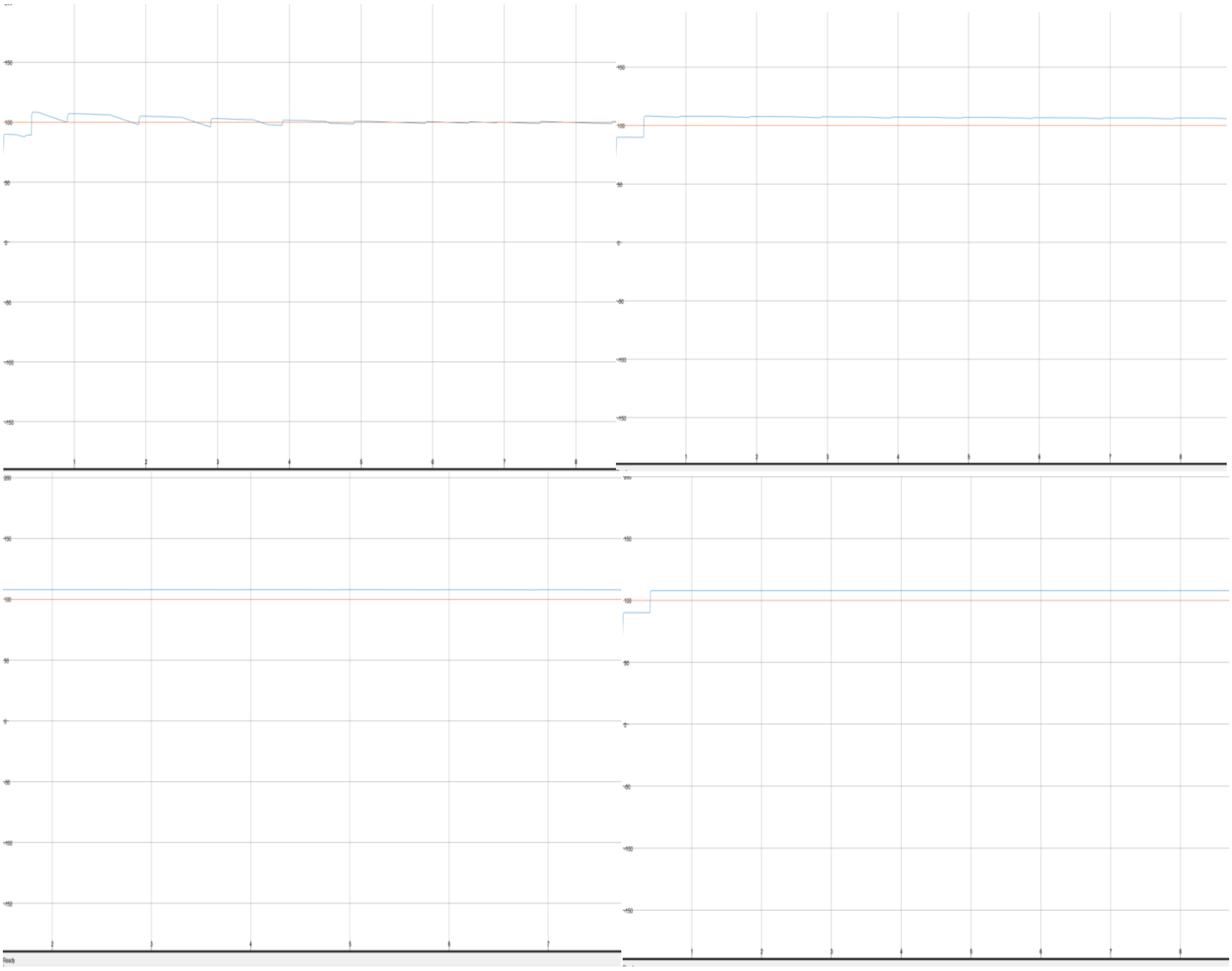

Fig. 7 DC-AC-DC transformation

Above is the input voltage and below is the output voltage. The yellow color represents the DC supply voltage and the blue color represents the final modulated voltage. When the load resistance is 50Ω and 500Ω respectively, the latter is obviously more stable than the former, and after analyzing the experimental simulation, it can be concluded that the larger the resistance is, the more stable the modulated voltage is.

5. Conclusion

Through experimental analysis and theoretical guidance, we used Simulink software to complete the design of the MCR-WPT circuit and the modulation of the waveforms, and found the characteristics of its transmission stability when the resistance value is large, which means that it has the opportunity to play a role in the field of wireless charging of power batteries in electric vehicles. Although there will still be harmonic components present, appropriate parameters and components can effectively reduce these problems, and we hope that new energy vehicles can realize wireless charging as soon as possible and further move towards intelligence.

References

[1] Wang J, Wang B, Zhang L, et al. Review of bidirectional DC–DC converter topologies for hybrid energy storage system of new energy vehicles[J]. Green Energy and Intelligent Transportation, 2022, 1(2): 100010.

[2] Zhang M. Research on dynamic wireless charging system design and charging control strategy for electric vehicles. Southeast University, 2021.

[3] Fichtner M. Recent research and progress in batteries for electric vehicles[J]. Batteries & Supercaps, 2022, 5(2): e202100224.

[4] Steinstraeter M, Heinrich T, Lienkamp M. Effect of low temperature on electric vehicle range[J]. World Electric Vehicle Journal, 2021, 12(3): 115.

[5] Koech K A, Mwandila G, Mulolani F. A review of improvements on electric vehicle battery. Heliyon, 2024, 10(15): e34806-e34806.

[6] Dong Y, Ma X, Wang C, et al. Research on Experimental and Simulated Temperature Control Performance of Power Batteries Based on Composite Phase Change Materials. World Electric Vehicle Journal, 2024, 15(7): 302-302.

[7] Zhai L, Shuangjie Y, Guixing H, et al. Modeling of conducted electromagnetic interference in electric vehicle motor drive systems. Journal of Beijing Institute of Technology, 2022, 42(08): 824-833.

[8] Zhai L, Lee G, Gao X, et al. Impact of Electromagnetic Interforance from Power Inverter Drive System on Batteries in Electric Vehicle. Energy Procedia, 2016, 88881-888.

[9] Cancan R, Lihui Y, Long L, et al. A Review of Metamaterials in Wireless Power Transfer. Materials (Basel, Switzerland), 2023, 16(17).

[10] Tao L. Circuit study of magnetic coupling resonant wireless charging system for electric vehicles. Southwest University of Science and Technology, 2021.

[11] Roslan M A A, Nanda N N, Yusoff S H. Series-series and series-parallel compensation topologies for dynamic wireless charging. IIUM Engineering Journal, 2021, 22(2): 199-209.

[12] Chen W. Review of research progress and application of magnetic resonant WPT technology. CSAA/IET International Conference on Aircraft Utility Systems (AUS 2022). IET, 2022, 2022: 10-17.