Research on deep sea radio energy transmission device based on LCC-S type compensation network

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Abstract

In this paper, the transmission characteristics of the system are analyzed for LCC-S type series resonant topology, and the parameters of the primary and secondary sides are matched according to the LCC transmission characteristics, and the primary side is matched as a constant current source and the secondary side is matched as a constant voltage source, and the series compensation is performed at the receiving end. This WPT device uses UCC21530 driver to realize full-bridge DC-AC high-frequency inverter, DSP to generate frequency adjustable PWM wave to control MOS tube turn-on and turn-off, and accurate processing of AMC1300 sampling to realize wireless communication between transmitter and receiver. The transmission efficiency of the LCC-S type wireless energy transmission system is verified by simulation, and the 500W wireless charging transmission device prototype is finally built to verify the functions of the studied prototype and further confirm the results of the theoretical analysis.

Keywords

LCC-S series resonant topology; compensation; WPT; wireless communication.

1. Introduction

Wireless power transfer (WPT) technology is a kind of technology based on non-wire and physical contact, which can directly transfer power from power side to load side. Wireless power transfer technology is free from the bondage of cables in the traditional power transmission process and does not require the direct contact of traditional wires, so it has the advantages of convenience, flexibility, safety and reliability that are incomparable with traditional power transmission methods. Most importantly, it can facilitate power supply in some special occasions, and has a wide application prospect in the fields of medical equipment, electronic products, underwater equipment, rail transportation and electric vehicles.

The current stage of radio energy transmission can use the electromagnetic effect or ultrasonic wave and other principles to complete the transmission of energy from the transmitting end to the receiving end. Among them, the use of electromagnetic effect of transmission can be divided into electromagnetic radiation (radio waves, laser),magnetic field coupling (inductive, resonant), electric field coupling and other three forms of transmission. Different transmission methods can meet different transmission distances and transmission power requirements [1].

Among them, Magnetic Coupling Resonant Wireless Power Transfer (MCRWPT) technology is a hotter research direction in the field of WPT technology because of its low dependence on transmission medium, long transmission distance, low directionality,high efficiency, high power, and high potential practical value.

The LCC-S type WPT system is widely used due to its advantages such as constant transmit current, high tolerance to unaligned coils, and high stability at open secondary or light load [2]. In this paper, the WPT system with LCC-S type compensation network is investigated and analyzed, and simulations are performed to verify and build the experimental prototype.

2. Principle and analysis of LCC-S type wireless energy transmission system

2.1. Principle of LCC-S type wireless energy transmission system

The magnetically coupled resonant radio energy transmission technology uses the principle of resonance through strong coupling resonance technology to achieve higher power (up to kW) and longer transmission distance of electrical energy. Figure 1 shows the schematic diagram of magnetically coupled resonant radio energy transmission system.

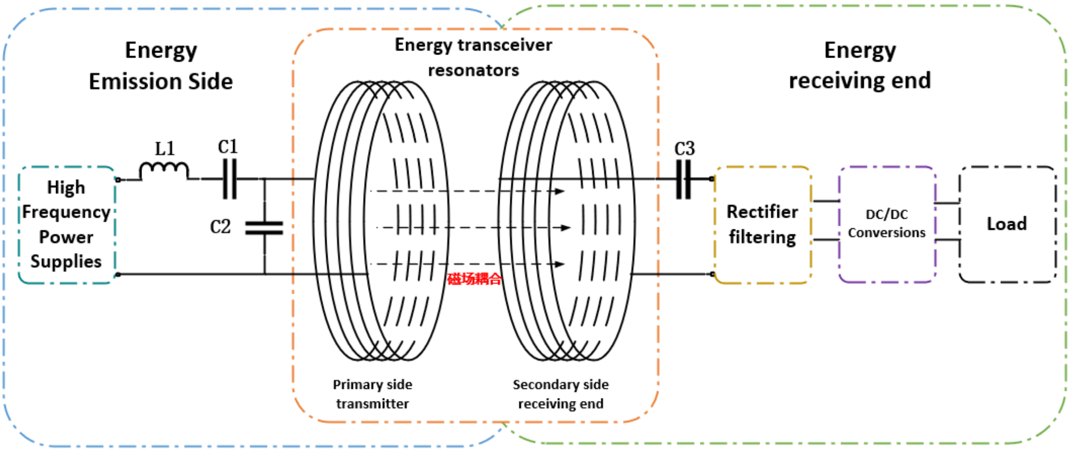

Figure 1: Schematic diagram of a WPT system

And the LCC-S type compensation network means that in the WPT system, the energy transmitter is compensated by LCC and the series (S) connection is used at the energy receiver. The circuit topology of the WPT system based on LCC-S type compensation according to the coupling theory is shown in Figure 2 below.

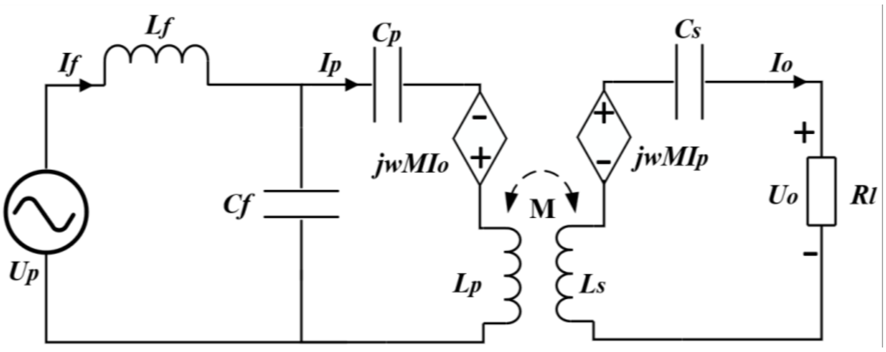

Figure 2: Equivalent simplified circuit model of LCC-S type compensation network WPT system

Where Figure 3 shows the equivalent simplified circuit model of the LCC-S type compensation network WPT system, U_S is the high frequency AC power supply, L_f is the transmitter compensation inductor, C_f and C_p are the transmitter compensation capacitors, L_p is the transmitter coil, L_s is the receiver coil, Cs is the receiver compensation capacitor, R_L is the load resistor, I_f is the current flowing through the compensation inductor L_f, I_p is the current flowing through the transmitter coil L_p, I_o is the current flowing through the load resistor R_l, and M is the mutual inductance between the transmitter and receiver coils[3].

According to Kirchhoff's voltage law (KVL), the following equation is obtained:

$$U_p = jwL_f I_f + \frac{1}{jwC_f}(I_f - I_p) \tag{1}$$

$$U_p = jwL_f I_f + \frac{1}{jwC_f}(I_f - I_p) \tag{2}$$

$$(\frac{1}{jwC_p} + jwL_p)I_p + \frac{1}{jwC_f}\left(I_f - I_p\right) - jwMI_o = 0 \tag{3}$$

$$-jwMI_p + (\frac{1}{jwC_s} + jwL_s + R_l)I_o = 0 \tag{4}$$

According to the resonance principle, when the system works in the resonance state, the following equation can be obtained:

$$jwL_f = -\frac{1}{jwC_f} \tag{5}$$

$$jw(L_p - L_f) = -\frac{1}{jwC_p} \tag{6}$$

$$jwL_s = -\frac{1}{jwC_s} \tag{7}$$

Based on the above resonance equation, the following current equation can be solved:

$$I_f = \frac{M^2 U_p}{L_f^2 R_l} \tag{8}$$

$$I_p = \frac{U_p}{jwL_f} \tag{9}$$

$$I_o = \frac{MU_p}{L_f R_l} \tag{10}$$

Based on the resulting current relationship, the voltage-current gain of the system is obtained as:

$$A_{uu} = \frac{U_o}{U_p} = \frac{M}{L_f} \tag{11}$$

$$A_{ui} = \frac{I_o}{U_p} = \frac{M}{L_f R_l} \tag{12}$$

$$A_{iu} = \frac{U_p}{I_o} = \frac{L_f R_l}{M} \tag{13}$$

$$A_{ii} = \frac{I_o}{I_p} = \frac{L_f}{M} \tag{14}$$

Where A is the gain of the system, the first subscript of A is the voltage or current at the transmitter, and the second subscript of A is the voltage or current at the receiver, e.g., A_ui is the gain of the current at the receiver and the voltage at the transmitter.

From the above gain equations (11) and (14), it can be seen that: A_uu and A_ii gains are independent of the load resistance, only A_iu and A_ii gains are related to the load resistance. Therefore, when the transmitter inputs a constant voltage, the receiver can also output a constant voltage; when the transmitter inputs a constant current, the receiver can also output a constant current; both will not change with the change of load resistance[4].

Also, the input impedance of the whole system:

$$Z_{in} = \frac{U_p}{I_f} = \frac{L_f^2 R_l}{M^2} \tag{15}$$

From the above equation, the input impedance of the whole system is purely resistive. When the system works at the resonant frequency, the inverter outputs pure active power to the load, at which time the system has the highest transmission efficiency, the maximum transmission energy and the best transmission performance.

3. LCC-S type wireless energy transmission system design

3.1. WPT system hardware design

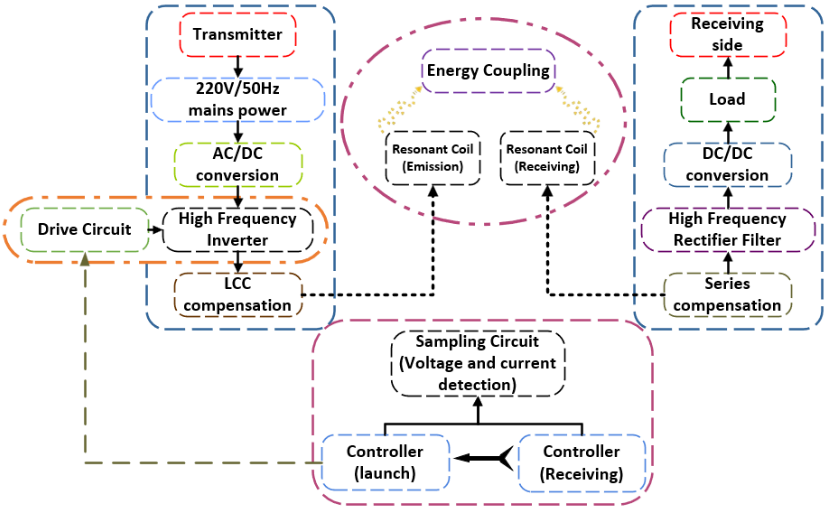

Figure 3: WPT system hardware structure block diagram of LCC-S type compensation network

The hardware structure block diagram of the whole WPT system is shown in Figure 3. The hardware structure of the system mainly includes: AC/DC converter circuit, high-frequency inverter circuit, driver circuit, control circuit, rectifier circuit, sampling circuit, compensation links on the transmitting and receiving sides, and resonant coils on the transmitting and receiving sides.

3.2. WPT System Topology Analysis

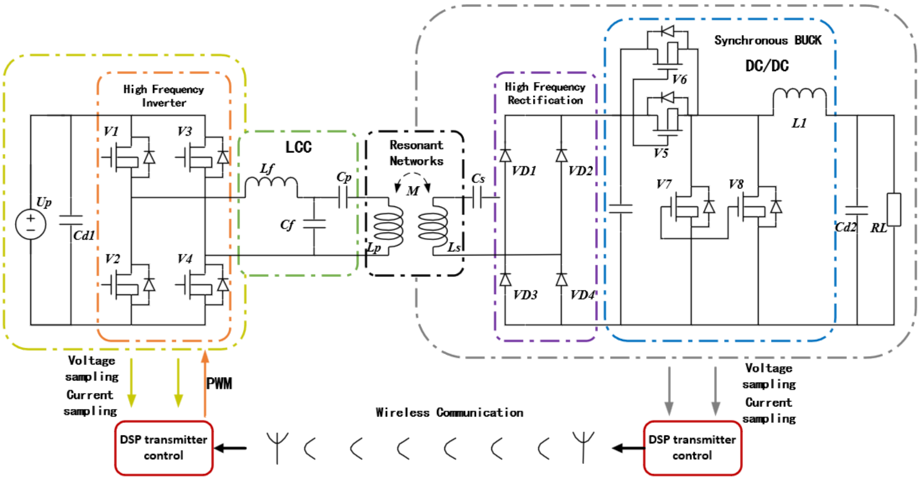

Figure 4: WPT system topology of LCC-S type compensation network

As shown in Figure 3, the WPT system topology of LCC-S type compensation network, the complete system consists of transmitter and receiver circuits. The transmitter side mainly consists of a DSP master control chip, a high-frequency inverter circuit, a sampling circuit, and an LCC resonant circuit. The high-frequency inverter circuit adopts a full-bridge structure to convert the input low-voltage DC into high-frequency AC; the sampling circuit is used to collect the bus voltage and bus current; the LCC resonant circuit is used to complete the construction of the resonant network at the transmitting and receiving ends. The receiver side is mainly composed of DSP main control chip, high frequency rectifier circuit, filter circuit, DC/DC converter circuit and sampling circuit. The single-phase bridge uncontrolled rectifier circuit is used in the high-frequency rectifier circuit to convert the coupled AC high-frequency signal into DC, and generate a stable DC voltage through the filter circuit, and finally get the desired voltage through the synchronous BUCK circuit; the sampling circuit is used to collect the current and voltage after rectification, and change the duty cycle of PWM through the feedback to the voltage and current, so as to change the output power[5].

3.3. High frequency inverter circuit design

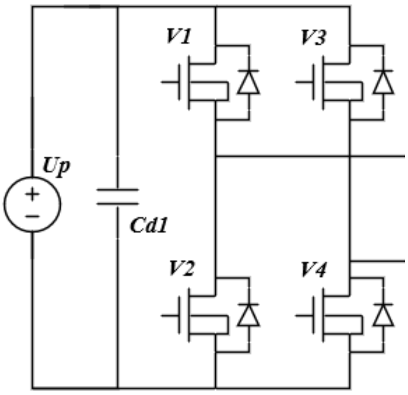

Figure 5: Voltage source full-bridge inverter circuit

The voltage full-bridge inverter circuit has four bridge arms, each of which consists of an IGBT and a diode connected in anti-parallel with it. It can be regarded as composed of two half-bridge inverter circuits, V1, V2, V3 and V4, which constitute the high-frequency inverter, where V1 and V4 turn on and off simultaneously, and V2 and V3 turn on and off simultaneously, and the two pairs alternate conduction by 180° to realize the energy inversion. In this system the high frequency inverter realizes the conversion of 48V DC power to 100kHz high frequency AC power.

3.4. Drive circuit design

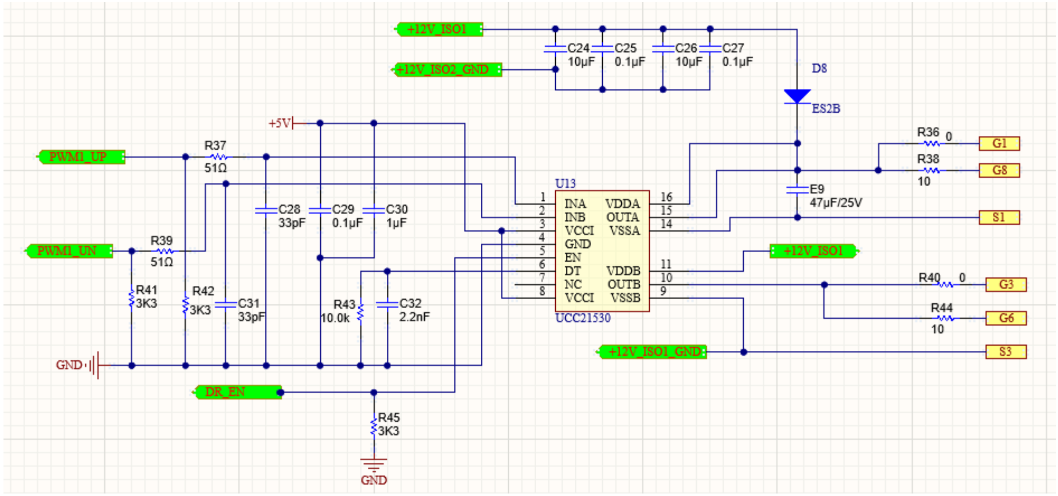

Figure 6: Drive circuit design

The PWM pulse signal is the control core of the WPT system. The control circuitry regulates the PWM output through the UCC21530 chip, which in turn controls the IGBTs of the high-frequency inverter. The UCC21530 is an isolated dual-channel gate driver with best-in-class propagation delay and pulse width distortion for high efficiency, high power density and robustness in a variety of power supply applications.

3.5. Sampling Circuit

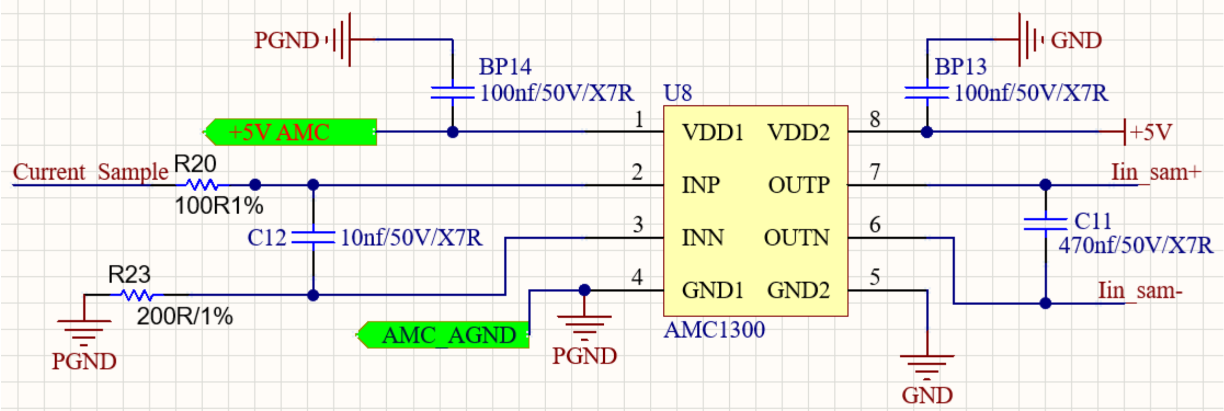

Figure 7: sampling circuit design

The bus voltage and current of this WPT system are sampled and processed in isolation by AMC1300, a precision isolation amplifier whose output is separated from the input circuit by a highly anti-magnetic interference isolation grid. The sampled voltage and current signals are amplified by LM358 op-amp processing and then sent to the DSP control unit.

3.6. DC/DC converter regulator circuit

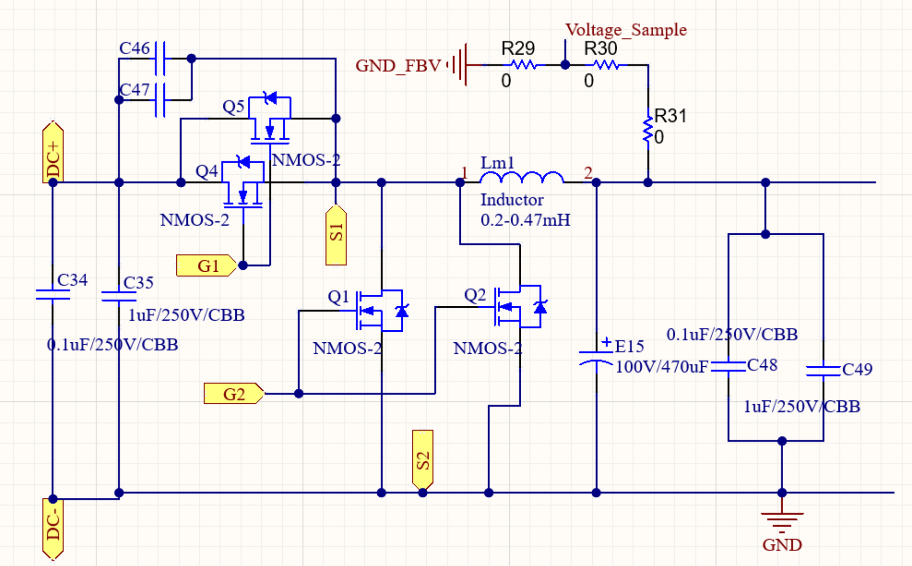

Figure 8: DC/DC conversion voltage stabilizing circuit

This WPT system uses a synchronous BUCK circuit topology to control the turn-on and turn-off of two MOS tubes through two PWM signals with the same frequency and complementary phases to finally stabilize the voltage output[6].

4. Simulation study validation

The full-bridge inverter output voltage and current waveforms, transmitter coil current waveforms, receiver coil current waveforms, and uncontrolled rectifier bridge input voltage waveforms are shown in the following simulation waveforms.

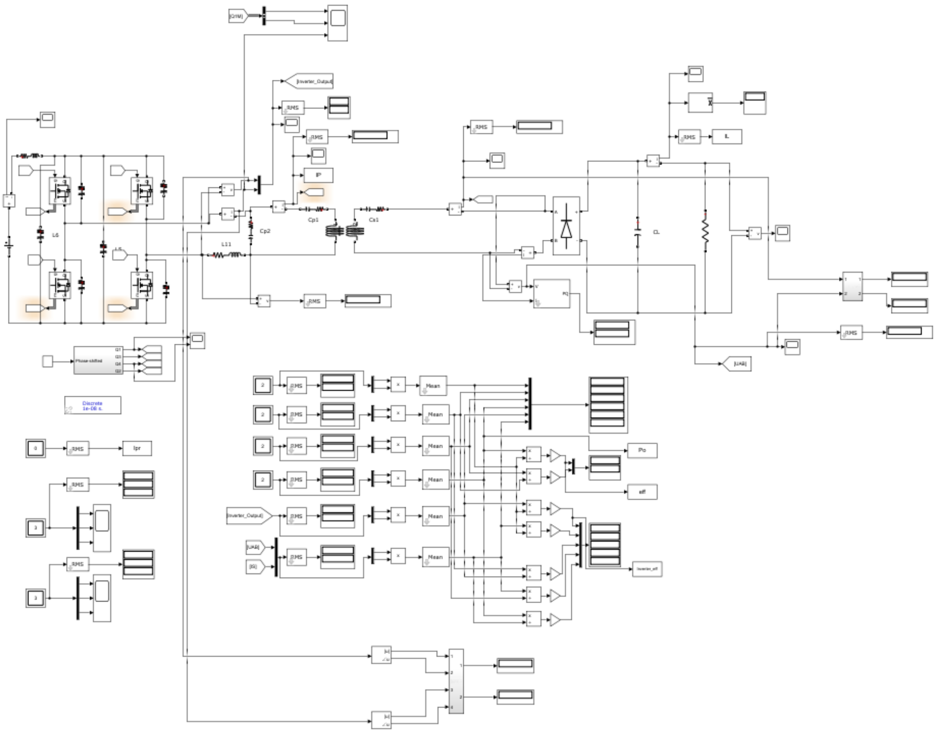

Figure 9: WPT system simulation construction of LCC-S compensation network

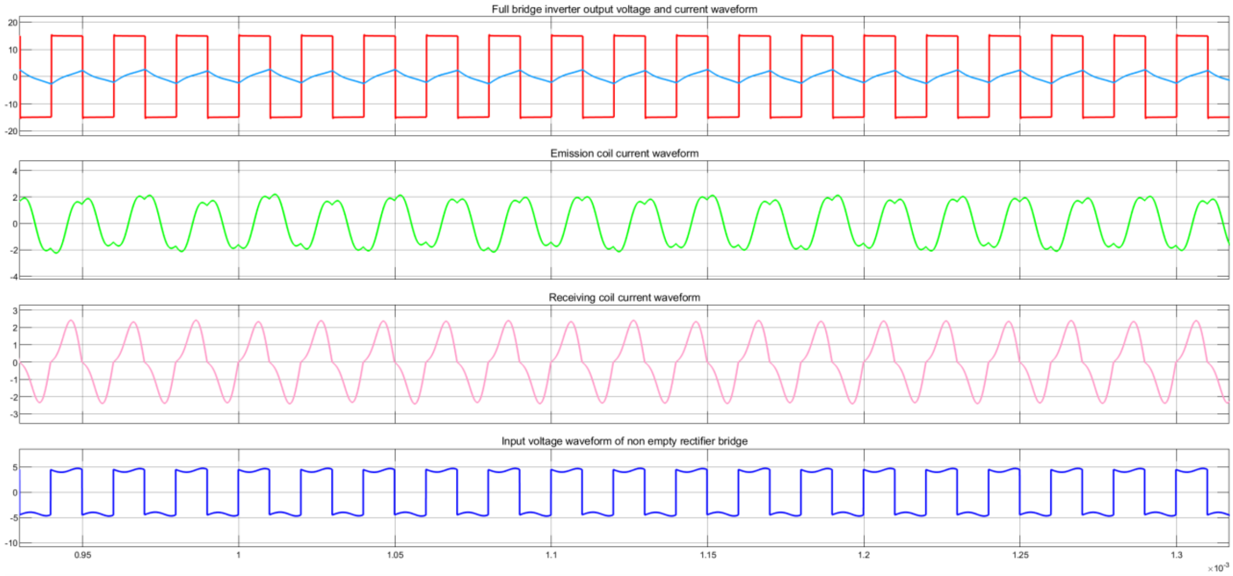

Figure 10: DC/DC conversion voltage stabilizing circuit

5. Experimental study to verify

By building the experimental prototype of LCC-S type WPT system, the prototype mainly includes DC power supply, high frequency inverter, LCC-S resonant network, full-bridge rectifier, digital oscilloscope and electronic load. The platform uses DSP as the controller of the primary and secondary sides, FDH055N15A as the MOS tube of the full-bridge inverter circuit, C3D16060 diode as the full-bridge rectifier, and USR-K6 module as the communication module. The following parameters are used for the experimental verification of this paper:

Parameters	Numerical value
U_{in}/V	48
$L_f/\mu H$	11.6
C_p/nF	54.2
C_f/nF	217.8
C_s/nF	47.4
$L_1/\mu H$	200

6. Conclusion

This paper analyzes the topology of the wireless energy transmission system of LCC-S type compensation network and verifies the feasibility of the wireless energy transmission device by building an experimental platform of 500W magnetically coupled resonant wireless energy transmission device.

References

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