

Research on Wireless Charging System Based on Photovoltaic Power Supply

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Abstract. Given the popularity of mobile devices and rapid advances in wireless technology, it is impossible to overlook how important charging methods should be as convenient and environmentally sustainable. This paper investigates the PV power supply integration in their wireless charging systems, which aligns well with developing an environmentally safe and renewable alternative for recharging that would alleviate pressure on conventional harvesting of electricity, while also improving ecological conservation and reducing carbon emissions following earlier interests. Firstly, based on the PV battery model modeling methods and fully considering light intensity conditions at various temperatures throughout a year-long experimental validation of the electrical output characteristics of these PV panels. Second, it adapts and optimizes DC-DC converters to the output of PV panels for higher energy conversion efficiency by stabilizing energy outputs due to weathering issues. Additional area for research includes the choice and tuning of Maximum Power Point Tracking (MPPT) algorithms that will enable this system to follow maximum power point under diverse weather and light conditions in order to maximize energy harvesting. Moreover, the paper also performs an in-depth study of coupling transformer design and optimization of main circuit parameters for better energy transmission efficiency and System stability. The feasibility and effectiveness of the PV-powered wireless charging systems are validated by simulation verification as well as experimental testing in this paper.

Keywords: Photovoltaic power supply system, wireless charging, DC-DC converter, MPPT algorithm.

1. Introduction

With the popularity of mobile devices and the development of wireless communication technology, the convenience and sustainability of charging methods have become the core of public attention. Traditional wired charging has limitations, such as the risk of equipment damage, which has prompted the rise of wireless charging technology to provide users with more flexible charging solutions. In addition, the application of renewable energy technology, especially photovoltaic power generation technology, has promoted the wireless charging system with photovoltaic as the power source to become the research frontier [1]. This combination not only reduces the dependence on the power grid but also reduces environmental pressure and carbon emissions, enabling innovative charging modes [2].

In the current situation, the literature on the academic exploration of photovoltaic powered wireless charging system is relatively limited, which provides a broad scope for research and significant significance for the selection of this research topic. In wireless charging technology, most researchers focus on improving loosely coupled transformers to enhance efficiency and range. They often ignore that these systems still rely on traditional power networks. This reliance leads to high energy consumption and environmental burden. Although there have been improvements in the design of loosely coupled transformers, there are still challenges in improving the power transmission efficiency and meeting the constant current and constant voltage output conditions.

In order to solve the above problems and existing challenges, this paper will first explore the photovoltaic cell model in detail, select or construct appropriate circuit models to predict its electrical energy output under various environmental conditions, and lay a theoretical pillar for system design and optimization. Then, it focuses on the design and optimization of DC-DC converter and then

adopts the appropriate MPPT algorithm, and integrates real-time light voltage and current data for feedback regulation, and the system can accurately track the maximum power point of the photovoltaic panel. In addition, regarding the core link of wireless charging technology, the first is to design a rectifier circuit module, which converts DC into AC to supply the wireless charging part. Next, the main circuit parameters and design are discussed and planned in detail to ensure the efficiency and reliability of the energy conversion process and reduce the loss in the energy transfer path. After that, the anti-interference structure was designed and optimized to achieve better energy coupling and transmission effects.

2. Photovoltaic Power Supply System Research

2.1. The Study of Photovoltaic Cell Model

A photovoltaic cell is a semiconductor device that uses the principle of the photoelectric effect to directly convert solar radiation into electricity. Its key performance parameters include open circuit voltage (V_{oc}), short circuit current (I_{sc}), fill factor (FF) and conversion efficiency [3]. The equivalent circuit model of photovoltaic cells has a single-diode model, a double-diode model, as shown in Fig. 1 and Fig. 2, and a more complex double-exponential model, which can describe the core characteristics of solar cells.

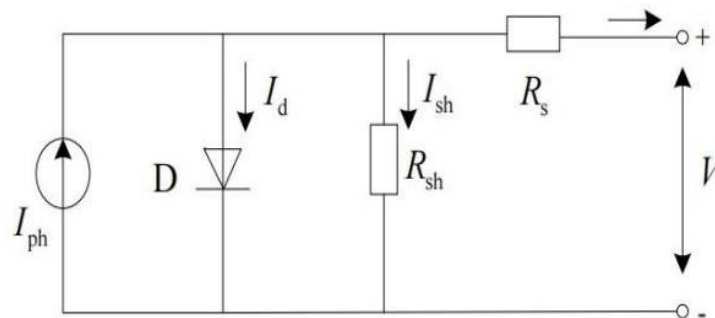


Figure 1. Equivalent circuit of a single diode model photovoltaic cell

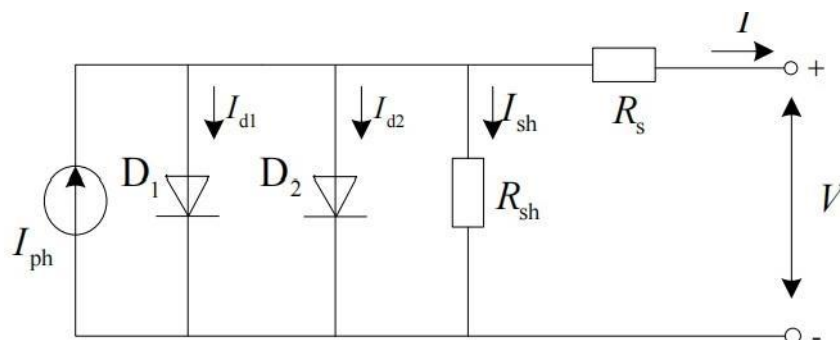


Figure 2. Equivalent circuit of double diode model photovoltaic cell

The electrical performance of photovoltaic cells is significantly affected by the change of temperature. As the temperature rises, the open circuit voltage V_{oc} of photovoltaic cells shows a downward trend, while the short circuit current I_{sc} mostly shows an upward trend [4]. The transient response of photovoltaic cells involves their rapid strain capacity when light conditions vary. This response includes current and voltage fluctuations due to shadow shading, cloud shading, or short-term changes in light intensity. And the agility of this reaction is crucial for the photovoltaic system to achieve maximum power point tracking (MPPT).

The efficiency and energy loss of photovoltaic cells play a decisive role in their performance and economic benefits in solar energy conversion applications. The energy loss of the battery mainly comes down to several key aspects: incomplete absorption of light, composite consumption of

electron-hole pairs, loss of light reflection and transmission, and energy dissipation caused by resistance. In practical applications, improving the efficiency of photovoltaic cells can be achieved by optimizing design strategies and improving manufacturing processes. Specific measures include enhancing the anti-reflective coating on the surface of the battery, adjusting the battery construction to the optimal state, and improving the purity of the material to reduce energy loss.

2.2. Research and Selection Of DC-DC Converter

When designing a wireless charging system based on photovoltaic energy, it is necessary to ensure that the voltage output of the photovoltaic panel matches the voltage demand at the receiving end of the wireless charging. Because the change in sunshine intensity and ambient temperature will directly affect the stability of photovoltaic panel voltage output, resulting in its output volatility. Therefore, the DC-DC converter plays a crucial role in this system, which can convert the unstable voltage output of the photovoltaic panel into voltage and current specifications that are both stable and meet the requirements of the system.

When choosing a voltage conversion scheme, the Boost converter is considered the preferred option. When the output voltage of the photovoltaic power generation unit fails to reach the voltage, standard required for the operation of the wireless charging system, the Boost converter can effectively raise the voltage to the required level, to fully meet the electricity demand of the charging system [5]. Conversely, Buck converters may have difficulty keeping the output voltage required. In addition, as shown in Fig. 3, the Boost circuit design is simpler and more intuitive than other circuit architectures such as buck-boost and cuk, reducing the number of components used.

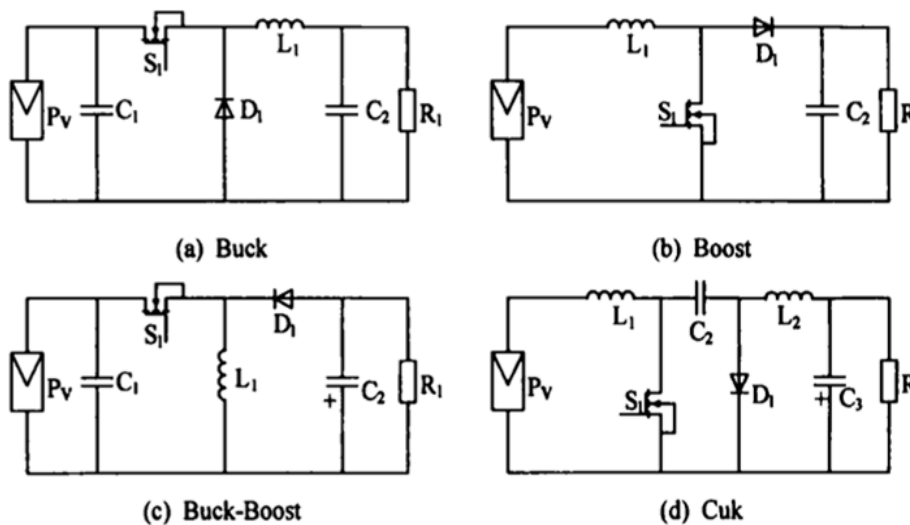


Figure 3. Four basic chopper circuits in photovoltaic power generation

For wireless charging systems using photovoltaic energy, the electromagnetic compatibility properties of DC-DC converters are also important. Specifically, in the DC-DC conversion of a photovoltaic system using the N-channel MOSFET in Fig 4 as an example, the drain-source voltage (VDS) encountered during actual operation is not an ideal trapezoidal signal form, but is prone to attenuating oscillations along the rising and falling edges, which will be accompanied by the formation of noise voltage. This can threaten the performance of adjacent electromagnetic devices and communication networks, and in severe cases can cause functional degradation and even equipment paralysis.

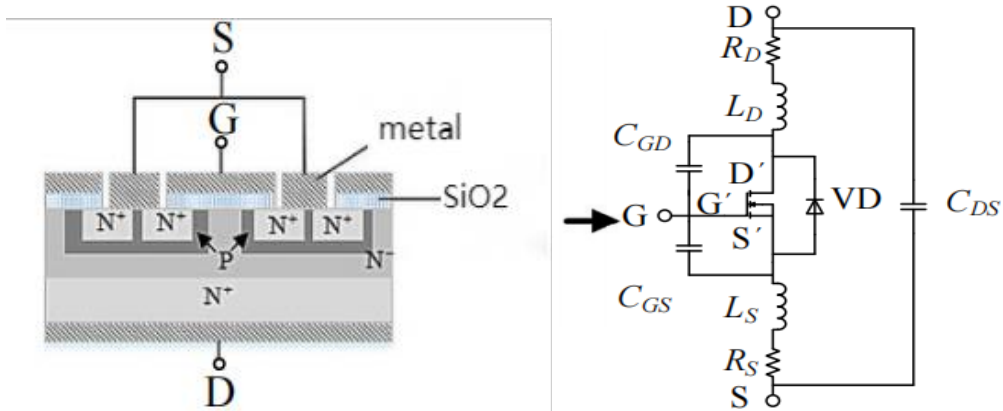
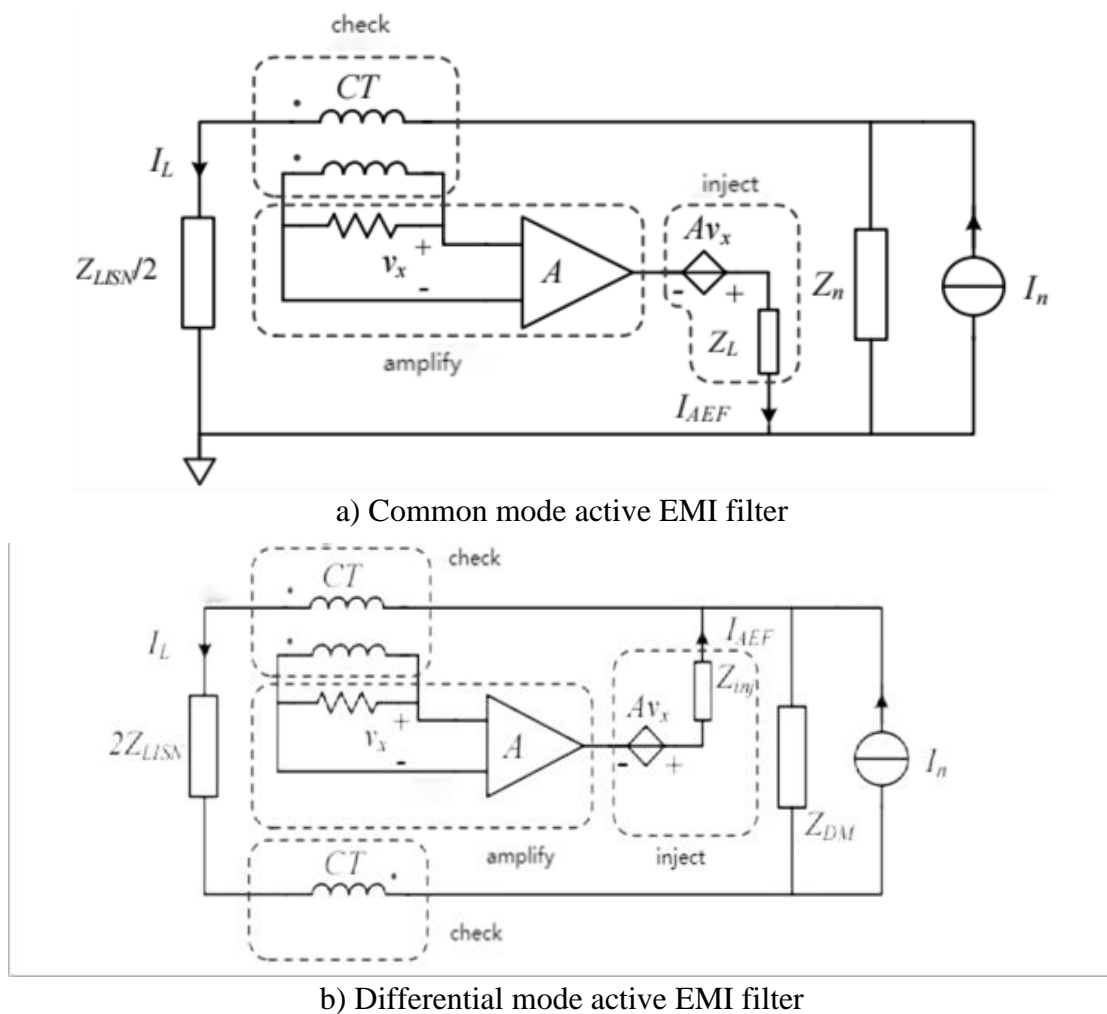


Figure 4. The structure of MOSFET and its equivalent circuit model

Therefore, when planning and implementing DC-DC converters, effective countermeasures such as optimizing routing strategy, integrating filter components and applying shielding are adopted to slow down or curb the generation of interference sources. In particular, the Boost circuit design shows greater efficiency in reducing electromagnetic interference output by more precisely tuning the action behavior of the switching element. In contrast, other DC-DC converter models, such as Buck-Boost or Cuk architectures, generally generate more significant high-frequency noise and electromagnetic emissions [6]. The attached fig. 5 shows several typical EMI filtering devices for DC-DC converters:



a) Common mode active EMI filter

b) Differential mode active EMI filter

Figure 5. Schematic diagram of working principle of common mode and differential mode active EMI filters

2.3. MPPT Algorithm Selection Optimization

2.3.1. Three kinds of MPPT basic algorithm

As shown in Fig. 6, the PV array, boost circuit, MPPT control algorithm module and load with the basic parameters set together constitute the following topology.

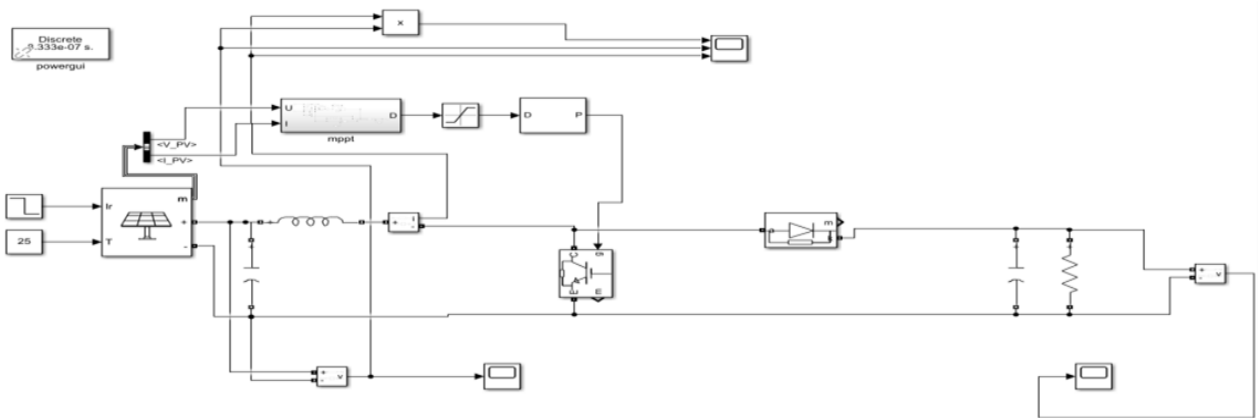


Figure 6. Topology of three basic algorithms for power conversion of photovoltaic and DC power grids

The constant voltage tracking strategy is designed to enable the photovoltaic panel to operate at a preset stable voltage level in order to track its maximum power output point. By maintaining this constant voltage state, it is continuously positioned at the maximum power point.

The conductance gain rule relies on the conductance characteristic of current voltage to realize the tracking function of maximum power point. As shown in the control strategy in Fig. 7, the system monitors the change of conductance and adjusts the operating voltage accordingly. When the variability of the output conductance is opposite to the value of the output conductance itself, that is, when the differential condition di/du is equal to $-i/u$, the solar cell module is in the maximum power output state [7].

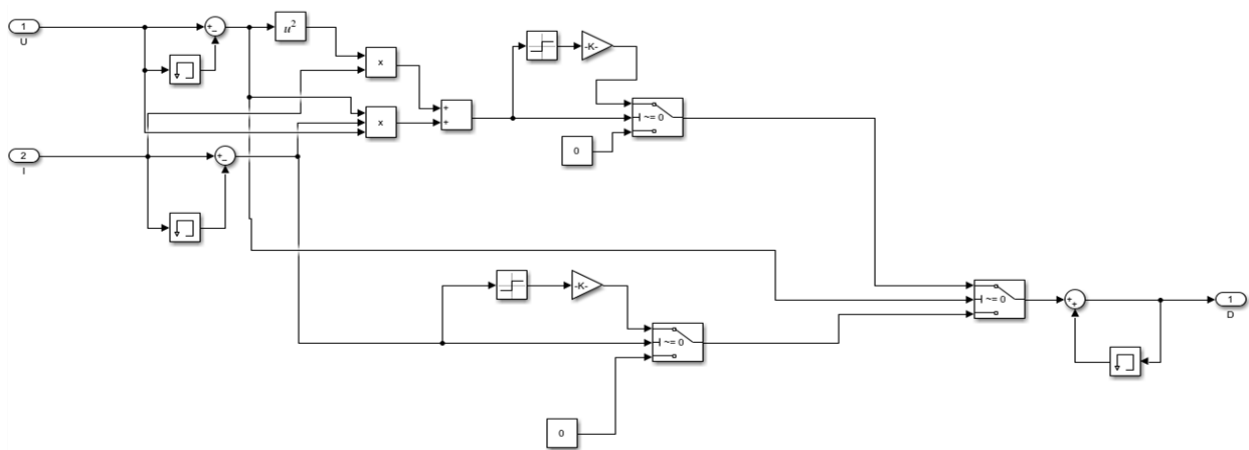


Figure 7. Control strategy of incremental conductance method

As for the disturbance observation strategy, the system performs maximum power point tracking by power variation. As shown in Fig. 8, the strategy process includes: At the initial time point t_1 , the output power of the solar panel P_1 is measured; Subsequently, a voltage change ΔV is applied via the processor signal, and after a time interval Δt , an updated output power P_2 is detected at time t_2 . According to the positive and negative guidance of the power difference $\Delta P = P_1 - P_2$, the system gradually adjusts the operating voltage ΔV until ΔP approaches zero.

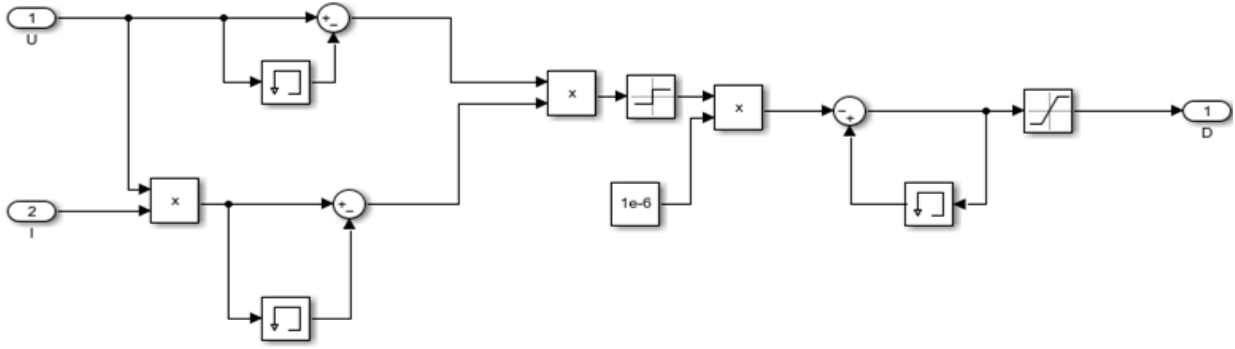


Figure 8. Control strategy of interference observation method

2.3.2. Optimization and application of particle swarm optimization

Particle swarm optimization (PSO) as a heuristic strategy, its design inspiration simulates the behavior patterns of biological clusters such as birds or fish. Similarly, the topology of Fig. 9 is basically the same as that of Fig. 6, consisting of a photovoltaic array with set basic parameters, boost circuit, PSO control algorithm module and load.

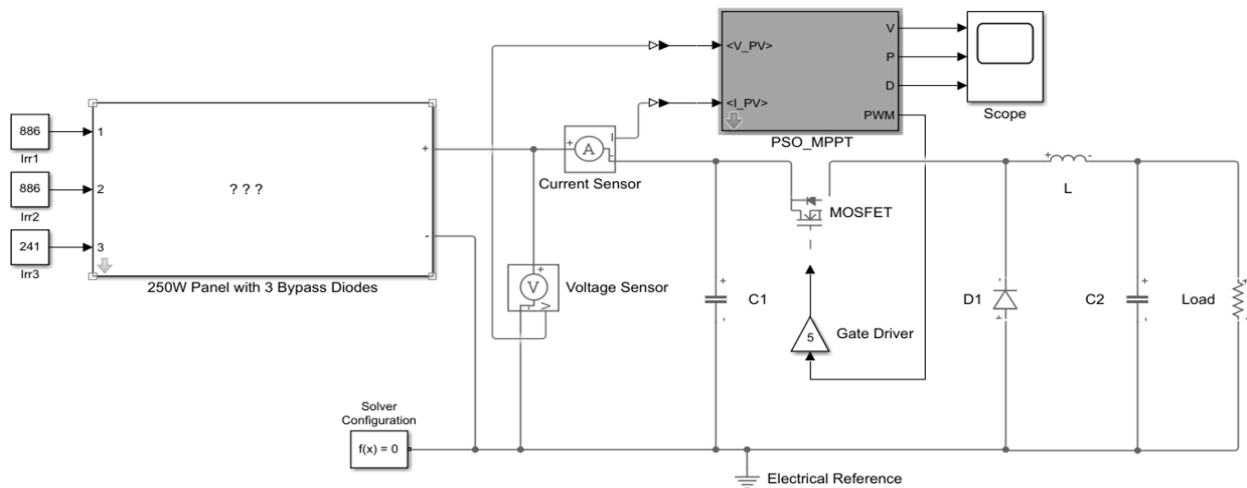


Figure 9. Topology based on particle swarm optimization

The PSO control strategy in Fig. 10 is as follows: It effectively explores the search space to approximate the global optimal solution through collaboration and competition among particles. When applying PSO to maximum power point tracking (MPPT) in a photovoltaic cell system, the search range of voltage and current is first defined, and the learning factors c_1 and c_2 are set to regulate the speed and direction of the particles. The particles then randomly initialize the position and velocity, evaluate the performance of each particle using the fitness function, and update its optimal position [8].

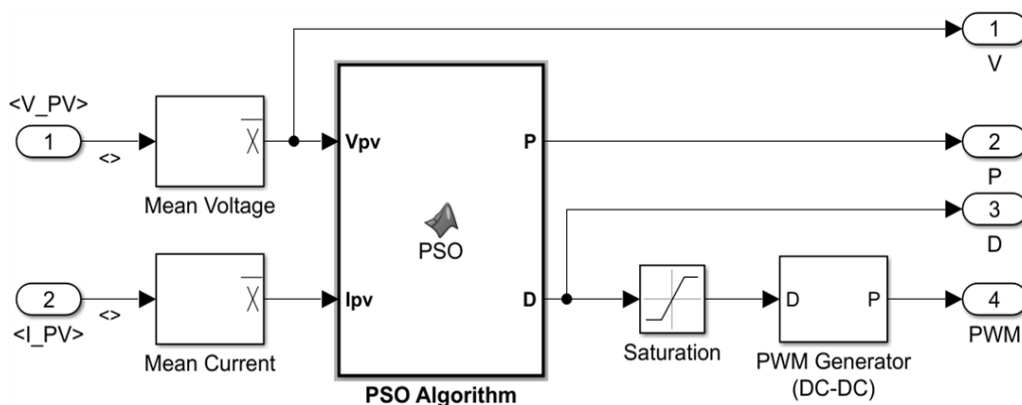


Figure 10. Control strategy of PSO

During iteration, the particle adjusts its position and speed according to update rules and reevaluates fitness values. If the particle finds a better position, its optimal position and the overall optimal value are updated. The process continues until the maximum number of iterations or accuracy criteria are met, and finally an estimate of the maximum power point is obtained.

3. Wireless Charging System Part System Analysis and Design

The key components of the radio energy transmission system include high-frequency full-bridge converters, transmitting coils, resonant coils, receiving coils, corresponding compensation capacitors, rectifier and voltage regulator components and charging devices [9]. The system works as follows: through a DC-DC conversion controlled by maximum power point tracking, the direct current generated by the photovoltaic panel becomes the system input, which is then converted by a high-frequency full bridge converter into high-frequency square wave AC and injected into the transmitting coil. The transmitting coil then converts this high-frequency square wave into the same frequency sine wave form, and establishes an electromagnetic energy transmission path with the resonance effect of magnetic coupling [1]. Through this path, the energy is transferred from the transmitting coil to the resonant coil, and then through the inductive coupling mechanism to the receiving coil. The energy received by the receiving coil is rectified and stabilized to effectively supply the required electrical energy for various charging facilities.

3.1. Design Of High Frequency Full Bridge Inverter

The inverter converts direct current to alternating current. As can be seen in Fig. 11, the high-frequency full-bridge inverter circuit is adjusted by using four switch components to precisely control its switching state and adjust the output AC waveform. PWM (pulse width modulation) control strategy is used to regulate voltage and precise control. In addition, high-frequency MOSFETs are the preferred switching devices for high frequency inverters due to their high switching speed and low on-loss. In addition, the inverter uses PWM strategy to generate high-frequency pulse signals and control the on-cycle of switching components to achieve fine management of AC voltage and frequency.

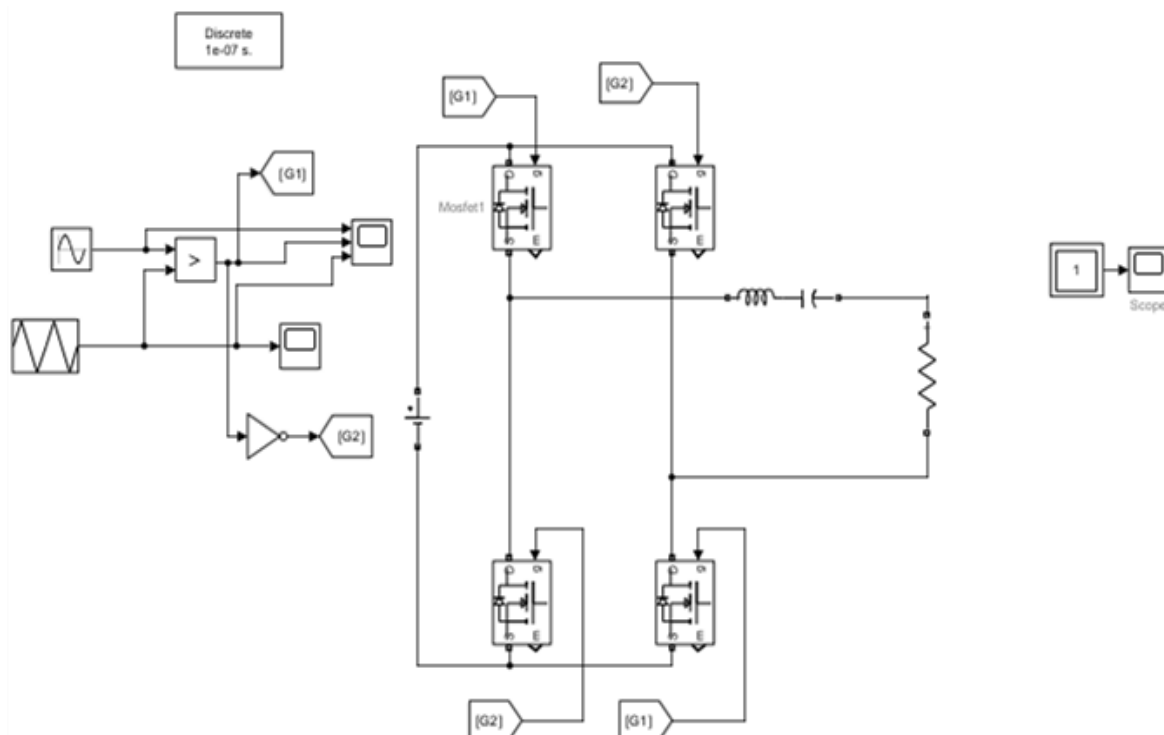


Figure 11. Single-phase high frequency inverter

3.2. System Model Analysis and Construction

The system adopts a triple coil architecture, the structure is envisaged as shown in Fig. 12, the components involve the transmitting coil, the resonant coil and the receiving coil. Compared to the two-coil configuration, this three-coil design enables longer transmission distances while maintaining the same power output and efficiency levels. In addition, compared with the four-coil structure, the three-coil layout presents a more simplified overall architecture and analysis path, and its decoupling steps are more straightforward [10].

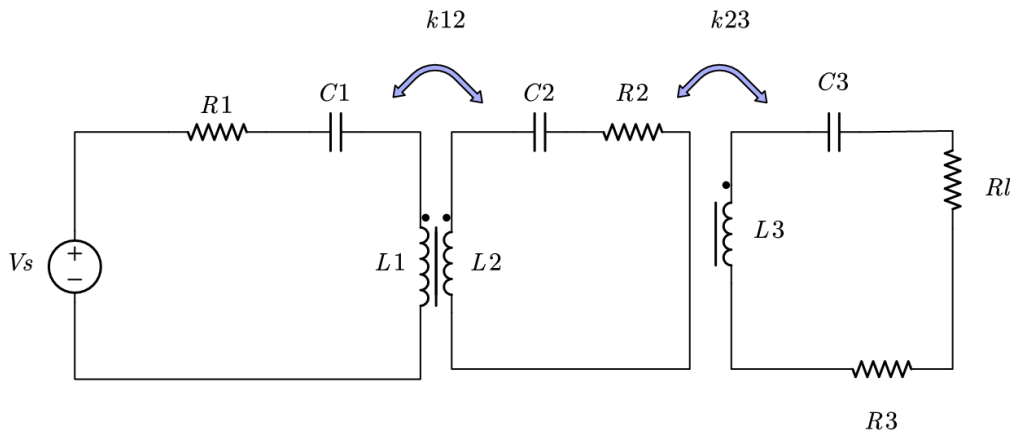


Figure 12. Three-coil structure system topology

Z_1 , Z_2 and Z_3 are defined as the impedance of the transmitting, resonant and receiving coil loops, which are expressed as follows:

$$\begin{aligned} Z_1 &= R_s + R_1 + j(\omega L_1 - 1/(\omega C_1)) \\ Z_2 &= R_2 + j(\omega L_2 - 1/(\omega C_2)) \\ Z_3 &= R_3 + j(\omega L_3 - 1/(\omega C_3)) \end{aligned} \quad (1)$$

In the above expression, R_s represents the internal resistance of the equivalent AC source; L_1 , L_2 and L_3 represent the inductance of the transmitting coil, the resonant coil and the receiving coil respectively. C_1 , C_2 and C_3 are the corresponding compensation capacitors respectively. Finally, R_1 , R_2 , and R_3 refer to the internal resistance of each coil.

The formula for this topology is:

$$\begin{aligned} I_1 Z_1 + j\omega M_{12} I_2 &= V_s \\ I_2 Z_2 + j\omega M_{12} I_1 + j\omega M_{23} I_3 &= 0 \\ I_3 Z_3 + j\omega M_{23} I_2 &= 0 \end{aligned} \quad (2)$$

In the formula, M_{12} represents the mutual inductance between the transmitting coil and the resonant coil, and M_{23} represents the mutual inductance between the resonant coil and the receiving coil. Since the receiving coils are in the same plane, mutual inductance between them is ignored. The distance between the transmitting coil and the receiving coil is far, so the mutual inductance between them is not considered. I_1 , I_2 , and I_3 are the current intensities flowing through the transmitting, resonating, and receiving coils, respectively.

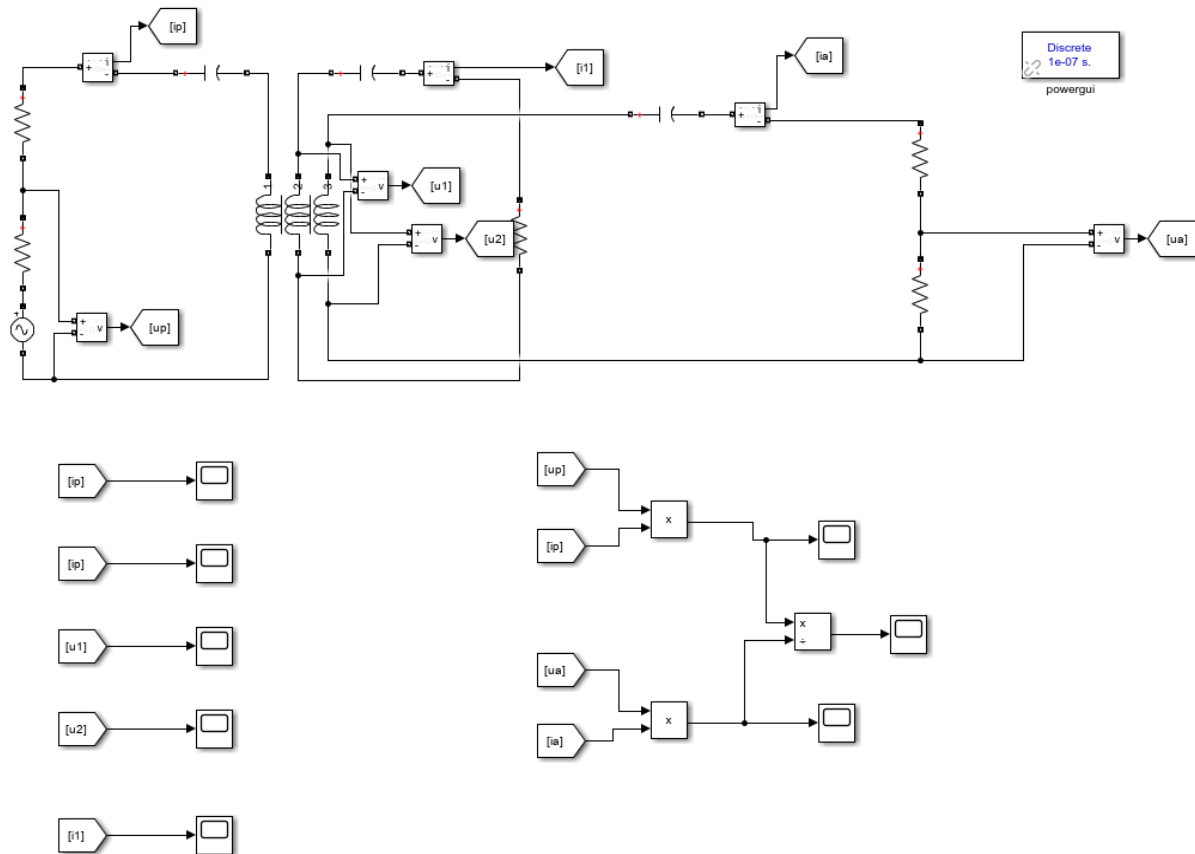


Figure 13. Simulation and construction of three-coil system model

Fig. 13 shows the simulation and construction of the three-coil structure in matlab. Assume that the coupling coefficients between each coil are ideal:

$$K_{xy} = M_{xy} / \sqrt{L_x L_y} \quad (3)$$

In the above equation, L_x and L_y represent the self-inductance of coil x and coil y , respectively.

In the formula, when the impedance Z_3 of the receiving loop and the mutual inductance M_{23} remain unchanged, the receiving coil current I_3 will rise with the increase of the transmitting coil current I_2 , thus increasing the output power of each receiving point. If the load on one receiving end changes, I_2 will also change, which will affect the current state of other receiving ends. According to the characteristic curve below, adjusting the equivalent load resistance R_l and coupling coefficient k_{23} at the receiving end will directly affect the RMS values of current I_1 and I_2 , as shown in Fig. 14. In particular, the fluctuation of current I_2 in the resonant coil can significantly affect the output level at the receiving end, showing the complex relationship between the internal parameters of the system.

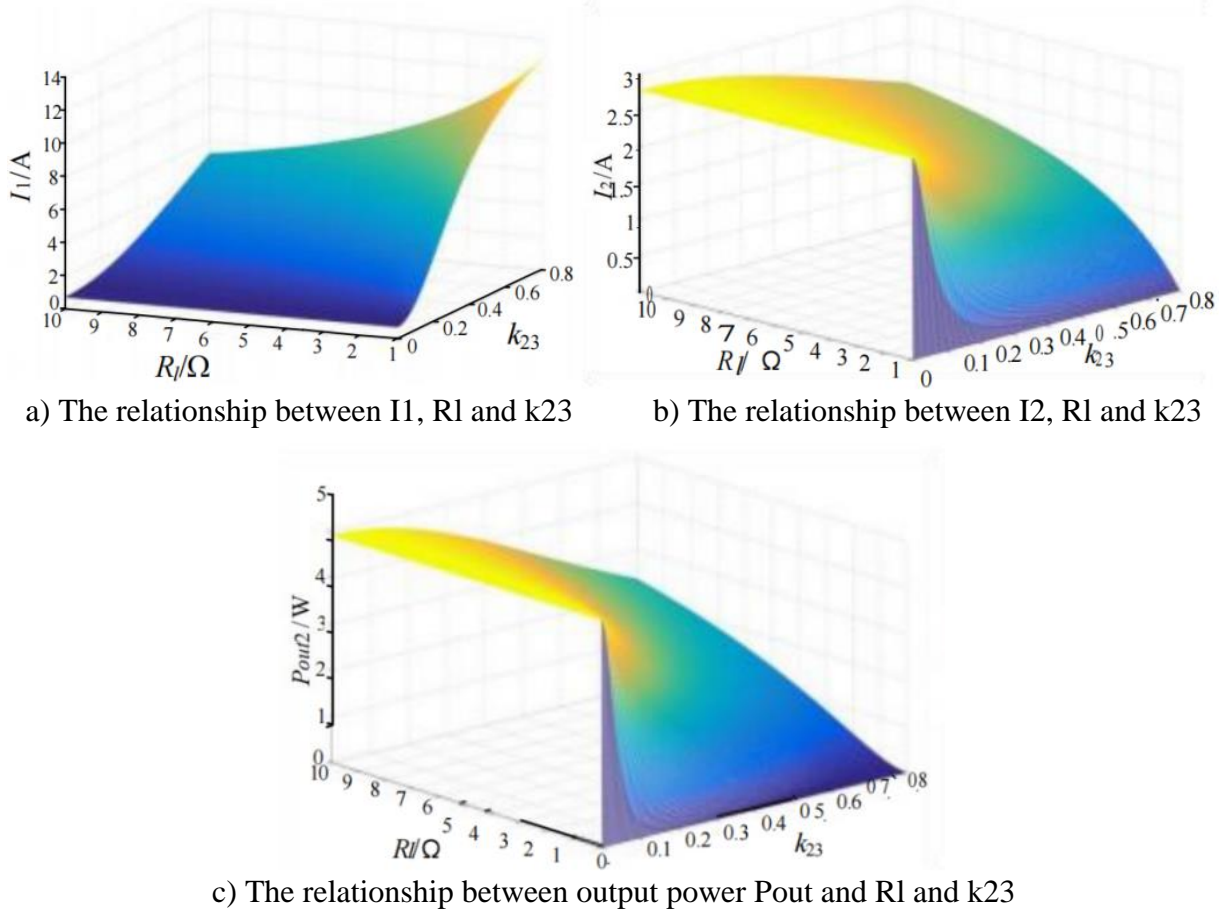


Figure14. Characteristic curve of multi-coil system [9]

3.3. System Anti-interference Structure Analysis And Construction

3.3.1. System anti-interference system main body construction

The SCC (Series capacitor compensation) mechanism occupies a core position in the field of wireless charging technology, and performs compensation operations by connecting capacitors in series on the transmission coil [11], thereby tuning the impedance characteristics of the transmission coil and enhancing the efficiency of energy transfer. Therefore, for the problem that the impedance matching of the equivalent circuit may be affected by the change of parameters at the receiving end, the SCC compensation structure and capacitor series are used in this study to optimize the performance. In addition, the system adopts a phase-shift adjustment mechanism to dynamically calibrate the compensation capacitance value at the transmitter [12], ensuring that the receiving coil can operate autonomously and maximize the energy receiving efficiency.

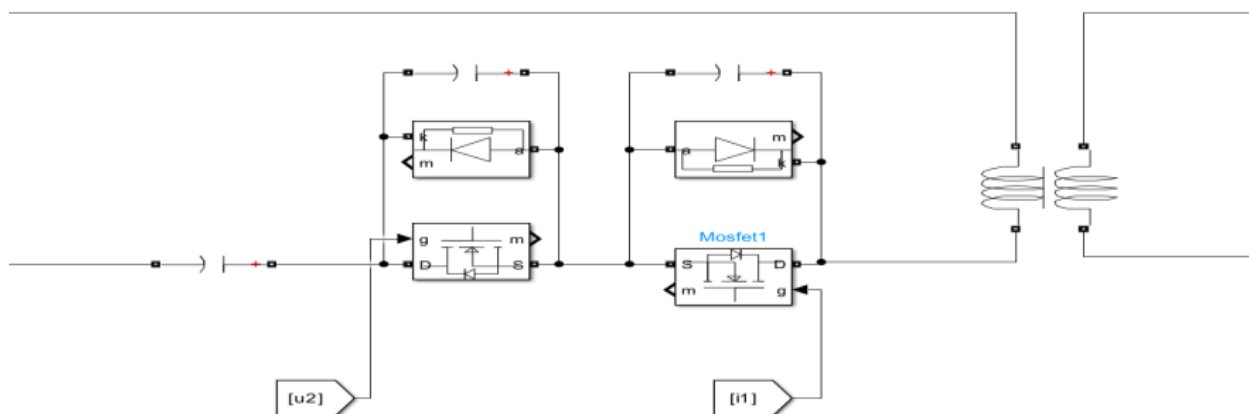


Figure 15. SCC and compensation capacitor series structure diagram

The SCC structure described in this paper is connected in series with the compensating element C1 at the transmitting end. As shown in Fig. 15, the original single-capacitor configuration is upgraded to a dual-capacitor system by juxtaposing two capacitors [1] on the reverse serial-connected switching device. By adjusting the drive pulse phase of the switching device in the SCC structure, the phase Angle of the switching device is different from that of the inverter switching device, so as to achieve the purpose of dynamic capacitance adjustment [12].

Equivalent capacitance of SCC and compensation capacitor C1 series structure:

$$C_{eq} = \frac{C_1 C_{p1,2}}{C_1 [1 - (a + \sin a) / \Pi] + C_{p1,2}} \quad (4)$$

In a multi-coil contactless power transmission system, when series capacitor compensation (SCC) architecture is used, the so-called phase shift Angle α refers to the phase difference between the switch element drive pulse and the inverter switch element drive pulse, and this Angle range extends from 0° to 180° [13]. By carefully regulating α , the effective management of the equivalent capacitance C_{eq} on the transmitting side can be achieved, and its adjustable range covers from 0.1 times C1 to C1 itself. It is worth noting that the dynamic change of C_{eq} will directly act on the inside of the resonant circuit and affect the performance of the current amplitude I2.

In the process of system operation, the maximum limit value of C_{eq} is mostly set at the resonant node of the receiving terminal. If the equivalent impedance is kept constant, the increase of parameter α leads to the increase of C_{eq} , which in turn increases the effective current intensity of I2. Therefore, by adjusting the phase shift Angle α inside the SCC structure, the current output of the resonant circuit can be mastered to ensure the stability of the wireless charging system under various operating situations.

In practical applications, this mechanism of adjusting the impedance of the transmission coil can significantly reduce the energy loss caused by changes in the parameters of the receiving end. For example, in a wireless charging system for electric vehicles, the SCC can respond to dynamic changes in battery status and maintain charging efficiency and system stability. In addition, the ability to dynamically adjust the compensation capacitance allows the system to adapt to different load conditions, which is particularly important for applications in multiple charging scenarios.

3.3.2. System anti-interference structure control strategy

The control strategy used involves several key parameters, including the control system reference voltages Vref1 and Vref2, and the sawtooth wave-like voltages Vc1 and Vc2. In addition, the output voltage produced by the PI controller is labeled V1, while the result obtained by applying the comparator to V1 and Vref2 is defined as V2.

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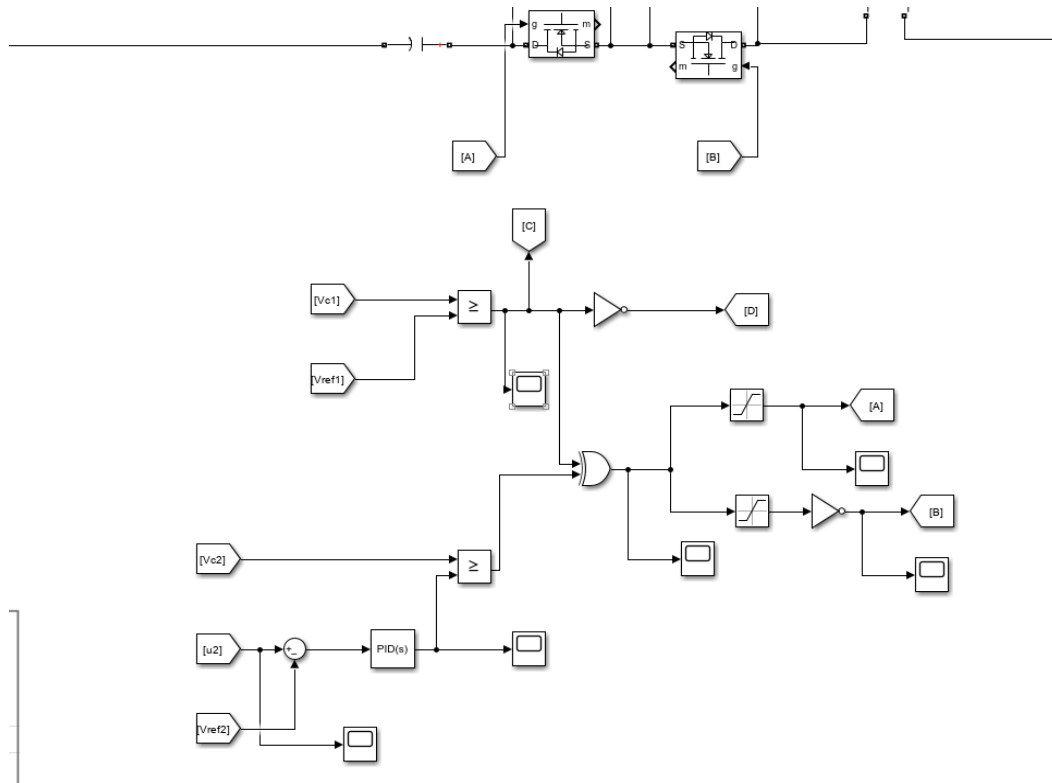


Figure 16. Anti-interference control logic diagram of multi-coil structure system

As shown in Fig. 16, when the voltage U_2 is lower than the reference voltage V_{ref2} , the voltage V_1 shows an upward trend; Conversely, if U_2 is higher than V_{ref2} , V_1 decreases accordingly. Through the comparator, V_{c1} and V_{ref1} are compared to generate the PWM1 waveform, which is responsible for modulating the activation and stop states of the full-bridge inverter circuit. In addition, the XOR operation of the PWM1 waveform and V_2 produces a PWM2 wave with the same frequency but a phase shift α , which is used to guide the on-off and cutoff of the switching elements in the SCC structure, where the magnitude of the phase difference α is directly determined by the value V_1 , each V_1 value corresponds to a unique α Angle. On the other hand, U_2 and V_{ref2} are regulated by the PI controller to ensure that U_2 can dynamically track changes in V_{ref2} , thus maintaining the voltage U_L2 on the load R_{L2} . Assuming that the position of the receiving coil L is fixed, it means that the mutual inductance M_{23} between the receiving coil is stable. Since the formula for I_2 involves U_L and M_{23} ($I_2 = jU_L / (\omega M_{23})$), it follows that the effective value of I_2 will remain constant when U_L and M_{23} are constant. Therefore, even in the face of changes in the equivalent impedance, the U_L is kept constant through active control, ensuring that the RMS value of I_2 is stable and unchanged, avoiding system overload and efficiency decline, and improving the overall system performance.

3.4. Wireless Charging Part System Efficiency Analysis

When the impedance of the receiving loop and the resonant loop are all equivalent to that of the transmitting loop, and assuming that both loops are resonating at their respective resonant frequencies, the equivalent impedance Z_{eq} is:

$$Z_{eq} = \omega^2 M_{12}^2 / (R_2 + \omega^2 M_{23}^2 / Z_3) \quad (5)$$

At the same time, according to the expression of equivalent impedance Z_{eq} , and then through the above topology and impedance formula, the input power and output power can be obtained through derivation and calculation:

$$P_{in} = V_s^2 (R_s + R_1 + \alpha) / [(R_s + R_1 + a)^2 + b^2]$$

$$P_{out} = \left[\omega^2 M_{12} M_{23} V_s / (Z_1 Z_2 + \omega^2 M_{12}^2 Z_1) \right]^2 R_1 / [(R_L + R_3 + Z_{eq})^2 + [\omega L_3 - 1/(\omega C_3)]] \quad (6)$$

In the above formula, Pin is the input power and Pout is the output power. The specific expression of a and b is as follows:

$$a = \frac{\omega^2 M_{12}^2 \left\{ R_{p2} (R_{p3} + R_l)^2 + \omega^2 M_{23}^2 (R_{p3} + R_l) + R_{p2} \left[\omega L_3 - \frac{1}{\omega C_3} \right]^2 \right\}}{\left[R_{p2} (R_{p3} + R_l) + \omega^2 M_{23}^2 \right]^2 + R_{p2}^2 \left[\omega L_3 - \frac{1}{\omega C_3} \right]^2} \quad (7)$$

$$b = \frac{\omega^4 M_{12}^2 M_{23}^2 \left[\omega L_3 - \frac{1}{\omega C_3} \right]}{\left[R_{p2} (R_{p3} + R_l) + \omega^2 M_{23}^2 \right]^2 + R_{p2}^2 \left[\omega L_3 - \frac{1}{\omega C_3} \right]^2}$$

Therefore, it is obvious that the final efficiency of the system in this part can be calculated by the formula $\eta = P_{out}/P_{in}$.

4. Conclusion

In this study, the performance optimization factors of photovoltaic cells, DC-DC converters and maximum power point tracking (MPPT) algorithm are analyzed to improve the energy conversion efficiency under different lighting conditions, so that the system can track the maximum power point more stably. In the research of wireless charging system, the high frequency full bridge inverter and SCC compensation structure are adopted, and the power transmission efficiency of the system is significantly improved, and the charging distance is realized by the three-coil design.

Future research could focus on the development of novel photovoltaic materials and technologies, such as perovskite photovoltaic cells and quantum dot solar cells, which have the potential to improve the conversion efficiency of photovoltaic systems and reduce costs [14]. In addition, it is possible to use new semiconductor materials and optimize the topology of the converter, helping to improve the overall system performance and efficiency. For wireless charging technology, research can be extended to more practical application scenarios such as electric vehicles, medical devices and drones, so that the technology can be more targeted.

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