

Efficiency Optimization of Circuitry-Free Wireless Power Transfer Systems via Full-Bridge Step Density Modulation and Maximum Efficiency Tracking

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Abstract: In recent years, Wireless Power Transfer (WPT) technology has experienced rapid development in fields such as electric vehicles, medical implant devices, and renewable energy scheduling. However, the efficiency of WPT systems is often limited by dynamic load variations and losses caused by hard switching. This paper proposes a collaborative optimization strategy integrating Full-Bridge Step Density Modulation (FB-SDM) with Maximum Efficiency Point Tracking (MEPT). Through theoretical derivation of maximum efficiency conditions and Simulink simulation verification, the FB-SDM modulation strategy dynamically adjusts the modulation ratio via voltage feedback without adding additional DC-DC converters, effectively reducing switching losses and achieving maximum efficiency point tracking. Experimental results indicate that, compared to traditional PWM modulation, FB-SDM reduces switching losses by approximately 50% at an output power of 64.5 W. Moreover, the system efficiency remains above 90% across all power outputs. The research presented in this paper provides a novel solution for the efficient and reliable operation of WPT systems, demonstrating significant engineering application value.

Keywords: Wireless Power Transfer(WPT), step density modulation (SDM), zero-voltage switching (ZVS), Maximum Efficiency Point Tracking (MEPT).

1. Introduction

Wireless power transfer (WPT) technology has been widely used in electric vehicles, consumer electronics, and medical equipment due to its advantage of transmitting energy without physical connections [1]. With the wide use of electric vehicles and portable devices, researchers have gradually been shifting their focus from low-power transmission to high-power, high-efficiency applications [2-3]. However, WPT systems still face issues such as low efficiency, high cost, and poor dynamic load adaptability, especially in scenarios where high power transmission is essential. Therefore, Achieving efficient and reliable power transmission has become a hot research topic [4].

In wireless charging systems, maximum efficiency point tracking (MEPT) technology is one of the core research directions aimed at improving energy transmission performance. Current research is primarily focused on impedance matching optimization and intelligent algorithm optimization. In terms of impedance matching, Yang et al. [5] introduced a DC-DC converter on the secondary side and combined it with a sliding mode controller to increase the bandwidth of the secondary DC-DC controller, thereby achieving load impedance matching. Zhao et al. [6] used a load estimation method

with a dual closed-loop controlled phase-shift H-bridge inverter to achieve maximum efficiency point tracking. In terms of intelligent algorithm optimization, machine learning methods have gradually become a research hotspot. Rafiei et al. [7] adopted a deep deterministic policy gradient (DDPG) deep learning method for energy management to adapt to complex dynamic loads and power supply conditions. Mahmud et al. [8] used machine learning to estimate load resistance and coupling coefficients in WPT systems using transmitter measurement data to help achieve maximum efficiency point tracking. However, it should be noted that the addition of intelligent optimization algorithms may significantly increase the system adjustment time. Impedance matching methods usually involve the introduction of DC-DC converters, which not only increase system complexity and cost but also reduce system efficiency due to losses generated by the converters themselves.

In the research of soft-switching technology for wireless charging systems, the focus is currently on improvements to system topology and the design of active clamp circuits. In terms of system topology improvement, Gu et al. [9] developed a PPT Φ_2 amplifier that achieved high-efficiency ZVS at 6.78 MHz through resonant network optimization. Li et al. [10] connected a resonant network branch in parallel at the inverter output, and the current generated by the parallel branch was used to charge and discharge the output capacitors of MOSFETs, thereby enhancing soft-switching characteristics. Tian Zihan et al. [11] proposed a method to adjust the parameters of the receiving-end compensation network to create a phase difference in the current flowing through the receiving coil, thereby achieving soft switching. In terms of active clamp technology, Li et al. [12] proposed a multi-MHz active clamp topology that achieved soft switching and increased power density by designing compensation capacitors and clamp capacitors. Pan et al. [13] proposed a novel pull-up active clamp wireless charging circuit that achieved soft switching by designing appropriate driving signals and clamp capacitors between the main switch and the auxiliary switch. It can be seen that the method of adding simple nonlinear components or combining them with driving signal modulation, with advantages such as low cost and compact size, is gradually becoming the mainstream method for achieving soft switching.

This paper proposes a strategy that combines maximum efficiency point tracking with full-bridge step density modulation (FB-SDM) in order to achieve soft switching and maximum efficiency point under load variations in WPT systems. The innovations of this paper are as follows:

- 1) Soft switching is achieved through a modulation strategy without additional components;
- 2) The modulation ratio is adjusted via voltage feedback to achieve maximum efficiency point, resulting in a simple and efficient system that effectively reduces costs.

Section II introduces the theoretical basis of series compensation, the mathematical derivation of maximum efficiency condition in WPT systems, and describes the FB-SDM modulation strategy and its implementation method; solutions of the soft switching problem and the issue of system deviation which caused by the load fluctuations will be presented in Section III; Section IV presents the simulation and experimental results; and finally, Section V summarizes the research results and proposes future research directions.

2. Theoretical research

2.1. Maximum Efficiency Condition

Because the coupling coils in wireless power transfer (WPT) systems generally exhibit a low coupling coefficient (k), the leakage inductance is relatively high and direct power transmission efficiency is very low. So, due to its ability to achieve greater efficiency and power density more effectively than other higher-order topologies, the series-series (SS) compensation topology is widely used. [14].

The SS compensation topology suppress the leakage inductance of the coils by connecting capacitors (C_1 , C_2) in series at the transmitting and receiving ends. The resonance condition is given by:

$$\omega_s = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \quad (1)$$

Where ω_s represents the resonant angular frequency of the system. By appropriately selecting L_1 , L_2 , C_1 , and C_2 , the system can attain optimal resonance at the target frequency, thereby maximizing the cancellation of leakage inductance.

In SS-compensated WPT systems, apart from the inverter switching losses, all other losses are approximately proportional to the square of the current. And the transmission efficiency formula of the WPT system can be expressed as:

$$\eta = \frac{\omega^2 M^2 R_{L,eq}}{\left[(R_2 + R_{L,eq})^2 + X_2^2 \right] R_1 + \omega^2 M^2 (R_2 + R_{L,eq})} \quad (2)$$

Where X_2 denotes the reactance of the secondary coil, L_1 and L_2 are the inductances of the primary and secondary coils respectively, R_1 and R_2 are the equivalent series resistances of the primary and secondary coils respectively, and $R_{L,eq}$ is the equivalent resistance of the secondary rectifier and load.

The efficiency of the WPT system is closely associated with the quality factor Q of the coils and the coupling coefficient k . By taking the derivative of the efficiency formula and setting it to zero, the maximum efficiency condition can be formulated as:

$$\eta_{\max} \approx \frac{k^2 Q^2}{\left(1 + \sqrt{1 + k^2 Q^2} \right)^2} \approx 1 - \frac{2}{kQ} \quad (3)$$

The system can reach maximum efficiency point when the load impedance meets the following condition:

$$R_{L,opt} = \sqrt{R_2^2 + \omega^2 M^2 \frac{R_2}{R_1}} \approx k\omega L_2 \quad (4)$$

In which k is the coupling coefficient, ω is the operating frequency, and L_2 is the self - inductance of the receiving coil. This approximation holds when $\omega^2 M^2 \gg R_1 R_2$, indicating that the maximum efficiency point is determined by k , Q_1 , and Q_2 , and can be achieved through coordinated parameter design.

2.2. Full - Bridge Step Density Modulation (FB - SDM) Modulation Strategy

To mitigate the additional losses caused by DC-DC converters, this paper proposes the utilization of a fully controlled rectifier bridge on the secondary side instead of the combination of a diode rectifier bridge and a DC - DC converter. As the rated operating frequency specified in the electric vehicle wireless charging standard is 85 kHz, traditional PWM modulation incurs significant losses due to hard switching at this frequency. Therefore, the Pulse Density Modulation(PDM) modulation method is typically investigated. However, this method presents two issues:

1) Since it adjusts the output power by modulating the pulse density, however, uneven pulse distribution leads to significant low - frequency ripple in the current.

2) Although switching between full - bridge and half - bridge modes can reduce current ripple, the prolonged off - state of some devices in half - bridge mode can cause severe non - uniformity in device losses.

To address these issues while fulfilling the conditions for soft switching, this paper designs a Full - Bridge Step Density Modulation (FB - SDM) based on the Pulse Density Modulation(PDM) modulation method. The structure of the FB - SDM modulator is depicted in Figure 1, which comprises a Sigma - Delta modulator, a finite state machine (FSM), and a multiplier. S1 and S3 are the switching signals transmitted to the two bridge arms, and the Sigma-Delta modulator dynamically adjusts the step sequence according to the output ratio (δ) of the FB - SDM modulation.

The FB - SDM modulation can satisfy the conditions for soft switching because the voltage step time is always synchronized with the current change time, and the resonant characteristics of the SS compensation topology enable the current to continue oscillating freely during the no - pulse period, thus maintaining the ZVS condition.

The full - bridge inverter has several switching states corresponding to different output voltage levels. According to the working principle of the inverter, the state transition diagram is shown in Figure 2, with three types of output steps: full - step (FS), generating $\pm V_{dc}$ steps; half - step (HS), generating $\pm 0.5V_{dc}$ steps; and level - hold (LH), outputting 0V. By rationally combining these step modes, precise control of the output voltage can be achieved, with the voltage target density (δ) defined as:

$$\delta = \frac{N_{FS} + 0.5N_{HS}}{N_{FS} + N_{HS} + N_{LH}} \quad (5)$$

Where NFS, NHS, and NLH are the number of half-cycles for full-step, half-step, and level-hold, respectively. Compared to PDM modulation, the FB - SDM modulation waveform includes half - steps in addition to full - steps, making the waveform composition more precise and smoother. At the same time, High - frequency noise is shifted to the high - frequency band by the Sigma - Delta modulator through integral error feedback, and the WPT system's bandpass characteristics naturally filter it out, which reduces output ripple.

Choosing a redundant transition strategy: when there are multiple redundant switching mode transition paths, adopt the path with the same color as the last transition is selected to prevent a MOSFET from being off or on for an extended period, balancing the losses of power devices. It also ensures waveform symmetry and avoids the accumulation of low - frequency harmonics. When the modulation Ratio changes from $\delta = 0.4$ to $\delta = 0.7$, the waveforms of the modulator signals are shown in Figure 3.

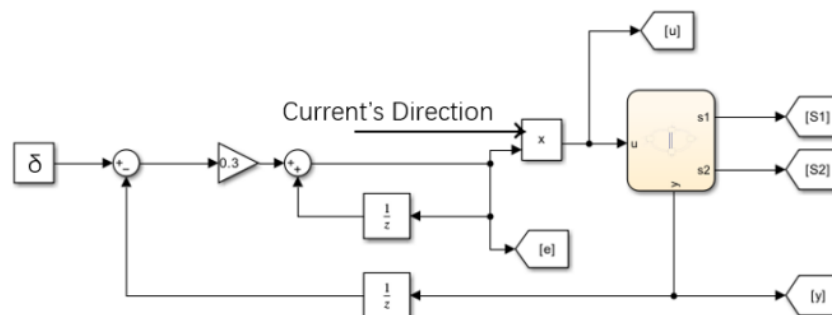


Figure 1: Structure of FB-SDM pulse generator

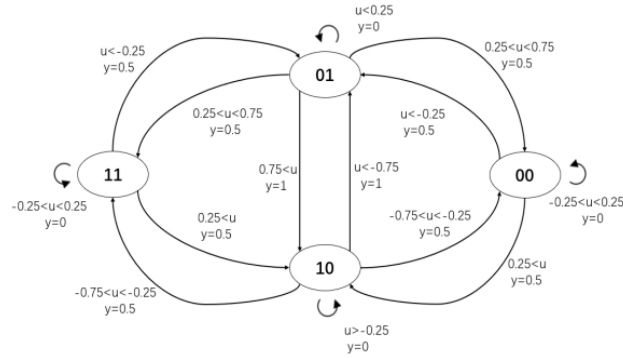


Figure 2: State transition diagram of FB-SDM state machine

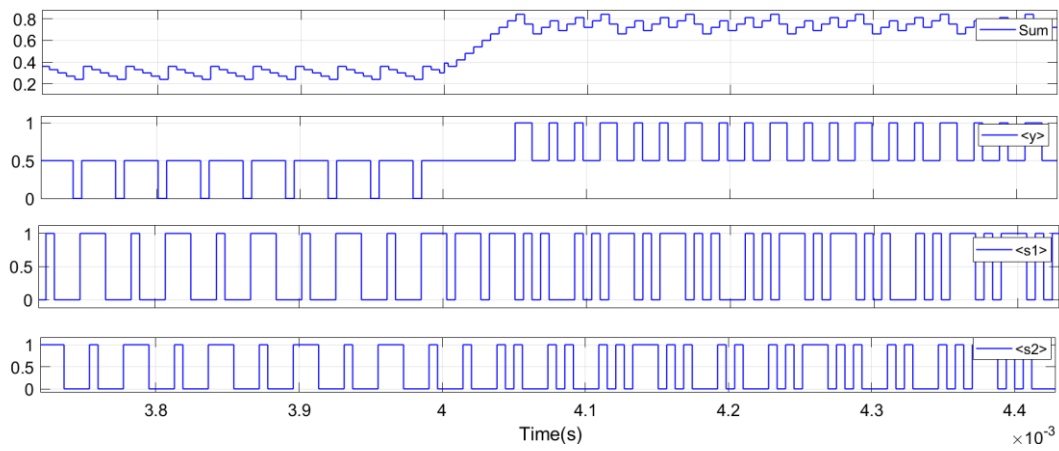


Figure 3: Waveforms of the modulator signals when δ changes from 0.4 to 0.7 under FB - SDM modulation

3. Maximum Efficiency Point Tracking

In practical applications, load impedance fluctuations caused by variations in the battery state of charge (SOC) or misalignment between primary and secondary coils (leading to reduced mutual inductance) can shift the system away from its maximum efficiency operating point [15]. This section elaborates on how the proposed strategy dynamically adjusts parameters via FB-SDM-controlled rectification and maximum efficiency point tracking to maintain optimal performance.

By regulating the modulation ratio δ ($0 < \delta < 1$) of the FB-SDM modulator, the equivalent load impedance at the rectifier input can be derived using the fundamental harmonic equivalence principle:

$$R_{L,eq} = \delta \frac{8}{\pi^2} R_L \quad (6)$$

Under the condition $\omega M \gg R_1 R_2$ the optimal load impedance simplifies to:

$$R_{L,opt} = \sqrt{\frac{R_2}{R_1}} \omega_0 M \quad (7)$$

Analysis of the SS compensation topology's input-output characteristics reveals that the voltage ratio between primary and secondary sides can be approximated by substituting the maximum efficiency load condition into the transconductance derivation:

$$\left| \frac{u_2}{u_1} \right| = \frac{\delta_2 U_{2,dc}}{\delta_1 U_{1,dc}} \approx \sqrt{\frac{R_2}{R_1}} \quad (8)$$

where $U_{1,dc}$, and $U_{2,dc}$ are the primary and secondary DC bus voltages, and δ_1, δ_2 are the modulation ratios of the primary and secondary FB-SDM controllers.

To achieve maximum efficiency point tracking, the secondary-side modulation ratio δ_2 is dynamically adjusted in response to load variations, ensuring compliance with Equation (8), while δ_1 is confirmed. This approach eliminates the need for modifications to the primary-side controller, which retains its original closed-loop voltage/current regulation. The search algorithm for the maximum efficiency point is illustrated in Figure 4.

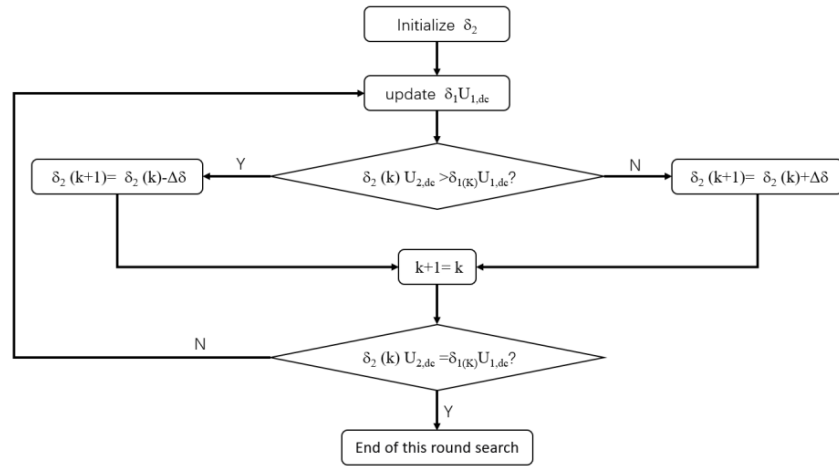


Figure 4: Maximum Efficiency Point Search Algorithm

Table 1: Parameters of simulated circuits

Parameter	Symbol	Value
Primary self-inductance	L1	310.2μH
Secondary self-inductance	L2	286.3μH
Primary capacitance	C1	11.1nF
Secondary capacitance	C2	12.1nF
Mutual inductance	M	57.8μH
Resonant frequency	ft	85.5kHz
Load resistance	R	40Ω
Output filter capacitor	Cf	20uf
DC bus voltage	Vdc	100V
Modulator sampling time	ts	5.848us
Modulator gain	K	0.3125

4. Simulation and Experimental Verification

To validate the feasibility of the proposed FB-SDM strategy, we developed a Simulink simulation model, which comprised by three main components: the WPT main circuit, modulation circuit, and control circuit. The electrical parameters of the transformer are listed in Table I. The WPT main circuit consists of a primary-side full-bridge inverter, a series compensation network, coupled coils, and a secondary-side full-bridge rectifier. The modulation circuit integrates a Σ - Δ modulator, finite

state machine (FSM), and harmonic generator, while voltage/current sensors and a flowchart-based control module formed the control circuit.

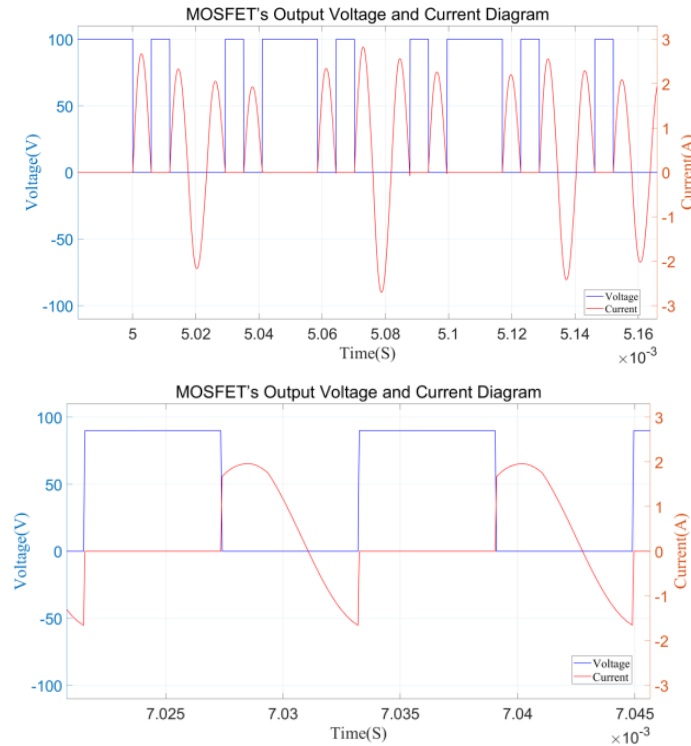


Figure 5: Current and voltage waveforms of MOSFETs under FB-SDM modulation (left) and PWM modulation (right)

Figure 5 compare the voltage-current waveforms of the MOSFETs under traditional PWM and FB-SDM modulation at an output power of 64.5 W. The results demonstrate that FB-SDM reduces switching losses by approximately 50% compared to PWM. This improvement is attributed to the synchronized voltage-current transitions enabled by FB-SDM, which minimize hard-switching effects

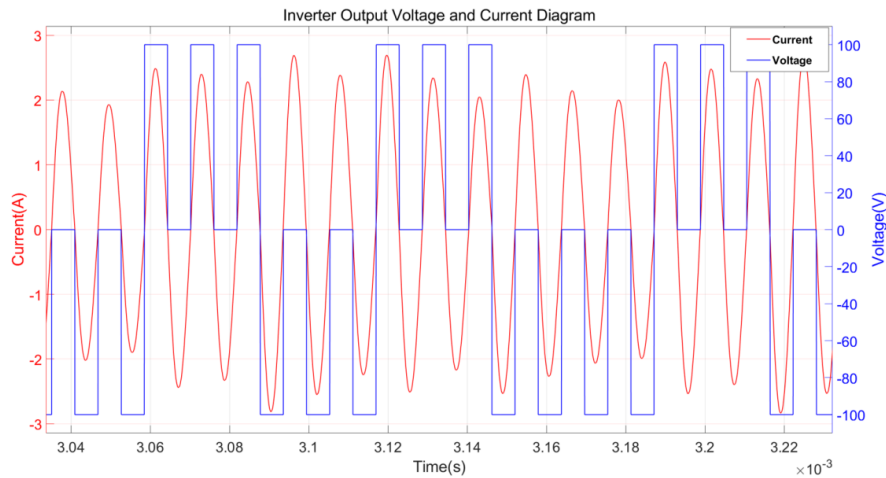


Figure 6: Inverter Output Voltage and Current Waveforms under FB-SDM Modulation at $\delta = 0.55$

Figure 6 illustrates the inverter's output voltage and current waveforms under FB-SDM modulation ($\delta=0.55$). The alignment of current commutation with voltage steps confirms the achievement of zero-voltage switching (ZVS), reducing switching losses significantly.

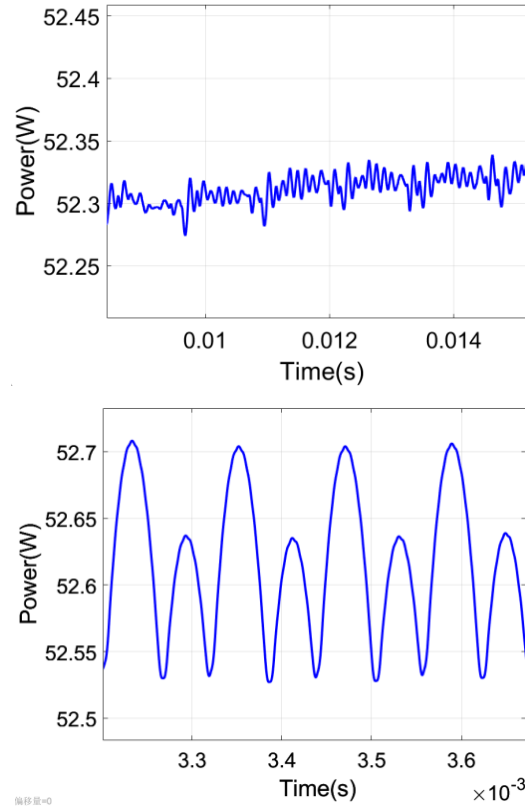


Figure 7: Power Ripple of System Output under FB-SDM and PWM Modulation

Figure 7 compares the output power ripple between PWM and FB-SDM modulation. While PWM exhibits a peak-to-peak ripple of 0.06 W, FB-SDM shows a slightly higher ripple of 0.17 W. This difference remains within acceptable limits, as FB-SDM's stepped voltage waveform (Figure 4) inherently introduces higher harmonic content compared to PWM's uniform square wave.

5. Efficiency Performance

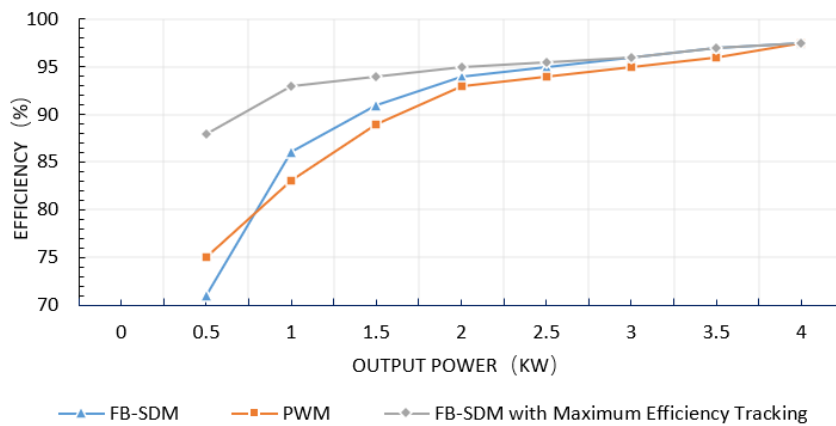


Figure 8: Efficiency characteristics under different control strategies

Figure 8 compares the efficiency curves when the secondary side uses diode rectification under PWM and FB - SDM modulation, as well as the efficiency curve using the maximum efficiency point tracking algorithm. Due to the better soft switching effect achieved, there is a significant difference in efficiency among the three methods. As the output power increases, the efficiency of the latter exceeds 90%. This is because when the secondary side converter uses diode rectification and the output power is low, the system efficiency will plummet due to the influence of the coupling mechanism. In contrast, in the WPT (Wireless Power Transfer) system using the maximum efficiency point tracking strategy, the controllable rectification on the secondary side can always maintain the equivalent load impedance at the optimal load.

6. Conclusion

This paper proposes a synergistic optimization strategy integrating full-bridge step density modulation (FB-SDM) with maximum efficiency point tracking (MEPT) to address critical challenges in wireless power transfer (WPT) systems, including soft-switching implementation and dynamic load adaptability. Theoretical analysis and experimental validation yield the following conclusions:

1.Component-Free Soft-Switching: The FB-SDM modulation strategy achieves soft-switching without additional components by synchronizing voltage steps with current transitions. Compared to traditional PWM modulation, switching losses are reduced by approximately 50% at an output power of 64.5 W, while system efficiency exceeds 90%.

2.Output Performance: While FB-SDM exhibits a slightly higher output power ripple (0.17 W peak-to-peak) compared to PWM (0.06 W), the trade-off remains acceptable given its advantages in efficiency and component stress reduction

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