# Maximum Energy Efficiency Tracking in a Wireless Power Transfer System Using Sigma Delta Modulated Controller

**R.V.S. Ram Krishna**

Department of Electrical Engineering, R H Sapat College of Engineering, Management Studies and Research, Nashik, India

**Abstract:** ***The emergence of Wireless Power Transfer (WPT) as a vital technology for contactless energy delivery for a wide variety of applications such as electric vehicles, biomedical devices, and consumer electronics is well documented. One of the key challenges in a WPT system is the achievement or retention of maximum energy efficiency under variable load and coupling conditions. This paper proposes a Maximum Energy Efficiency Tracking (MEET) method based on Sigma-Delta modulated Pulse Density Modulation (PDM), aimed at dynamically adapting the power transfer to changing operating conditions. The proposed method uses the precise control capability of sigma delta modulation to finely adjust pulse density and thus dynamically change the operating point to ensure optimal efficiency of the system. Simulation results validate the effectiveness of the proposed method and demonstrating improved system efficiency for all load conditions.***

**Keywords:** Wireless Power Transfer (WPT), Maximum Energy Efficiency Tracking (MEET), Sigma Delta Modulation (SDM)

## 1. Introduction

Wireless Power Transfer (WPT) technology is now quite well established as a discipline and its potential to power devices without the need for a physical connection is well appreciated. Developments in academia and industry highlighting its applications in electric vehicles, consumer electronics, biomedical implants, and underwater autonomous systems can be seen in the available literature. The efficiency of WPT systems is a critical performance metric, and achieving Maximum Energy Efficiency Tracking (MEPT) remains a major challenge, particularly under dynamic load and coupling conditions.

In this context, Pulse Density Modulation (PDM) has emerged as a promising control technique to enhance the efficiency of a WPT system. It does so by modulating the pulse rate of the converter switches rather than varying the amplitude or frequency of the signal. Li et al. [1] proposed a novel PDM strategy that modulates the pulse density in real-time to track the maximum efficiency point, showing significant improvements in energy transfer. Zhong and Hui [2] further established a framework for MEPT and demonstrated its implementation in typical WPT systems.

In [3], the secondary-side controlled PDM mechanism was improved by Yenil and Cetin by using an LCC-S compensation network, enhancing system robustness and output regulation. Wang et al. [4] incorporated PDM with feed-forward power compensation resulting in an improved communication performance via FMPSK in WPT systems. Unal et al. implemented an irregular PDM control method to achieve constant current and voltage outputs, focusing on the non-linearity in load conditions [5]. A load-adaptive delta sigma PDM technique with frequency tuning, suitable for class-D high-frequency inverters, improving Zero Voltage Switching (ZVS) and efficiency was proposed by Mishima and Lai in [6]. Ye et al. proposed a PDM control mechanism for maintaining constant output voltage across multiple loads in magnetically coupled resonant systems [7]. The design of a low-subharmonic PDM strategy that operates efficiently over a wide modulation range for full-bridge converters was discussed in [8]. In the domain of marine applications, Ma et al. presented a hill-climbing and golden section search hybrid algorithm for MEPT in underwater vehicles, integrating PDM within their optimization loop [9]. A multi-level control scheme employing Particle Swarm Optimization (PSO) to improve WPT system performance was proposed in [10].

Some other MEPT algorithms discussed and elaborated in the literature are mentioned in references [11-20]. These include methods for battery charging applications [11], methods based on Generalized State Space Averaging (GSSA) model [12], methods utilizing input voltage control for improved adaptability [14], load side efficiency tracking [15] and dual frequency PDM methods [17, 20]

The progress indicates the evolution of PDM-based MEPT strategies in WPT systems ranging from control algorithms, converter design, compensation network improvements, and optimization techniques, collectively contributing to the realization of high-efficiency wireless power transfer under diverse operating environments. In this paper, a method for efficiency tracking (maximum efficiency retainment) is elaborated which utilized the sigma delta technique of pulse density modulation for voltage control. The method demonstrates the achievement of maximum efficiency for widely varying load conditions.

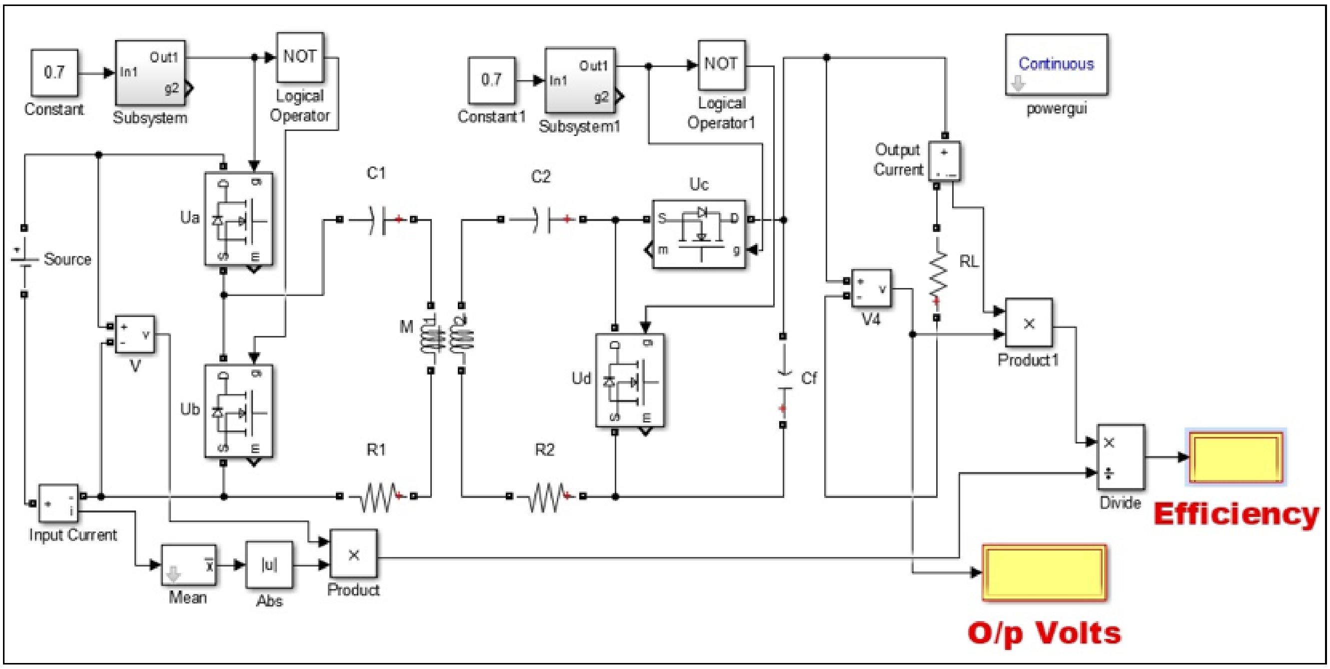



**Figure 1:** MATLAB / SIMULINK Model of the WPT System

## 2. Block Diagram

In the proposed system, the maximum energy efficiency of a wireless power transfer system is tracked using a pulse density modulation scheme based on "sigma delta modulation". In this section, the various blocks comprising the system are detailed in terms of their architecture and inter connection.

**System Overview**

The proposed WPT (Wireless Power Transfer) system comprises of the following key subsysterms

- DC Power Supply
- Half-Bridge Inverter with Pulse Density Modulation using Sigma-Delta Modulation
- Series-Series Compensated WPT Link
- Rectifier and Load at Receiver Side

A MATLAB SIMULINK block diagram of the proposed system is shown in Figure 1. Among the various compensation topologies available such as series-series, series-parallel, parallel-series and parallel-parallel, the series-series compensated topology is used for both transmitter and receiver sides to maximize power transfer at the resonant frequency. The system parameters are summarized in Table 1.

**Table 1:** Model Parameters

| Parameter | Value |
|---|---|
| Transmitter coil inductance ($L_1$) | 75.3 µH |
| Receiver coil inductance ($L_2$) | 75.3 µH |
| Compensation capacitance ($C_1$, $C_2$) | 400 pF |
| Operating frequency ($f_0$) | 100 kHz |
| Mutual inductance (M) | 0.8 µH |
| Load resistance ($R_l$) | 100 Ω (variable) |
| Input voltage (V_in) | 50 V (DC) |

As the name suggests, a series – series resonant WPT system consists of a resonant coil (having inductance) in series with a resistor and a capacitor. The circuit resonates at a frequency given by

$$f = \frac{1}{2\pi\sqrt{LC}}$$

For the given parameters, this resonance frequency comes out to be nearly 920,000 Hz which lies in the upper ISM band and is quite popular for several WPT applications. The mutual inductance between coils varies with spatial alignment, affecting energy transfer efficiency.

The variation of the output voltage and efficiency with respect to the operating frequency is shown in Figure 2. As can be seen, both the voltage and efficiency show a peak near the designated frequency of 920000 Hz (920 kHz) and this shows the sensitivity of the series – series compensated resonant inductive wireless power transfer system to the operating frequency.

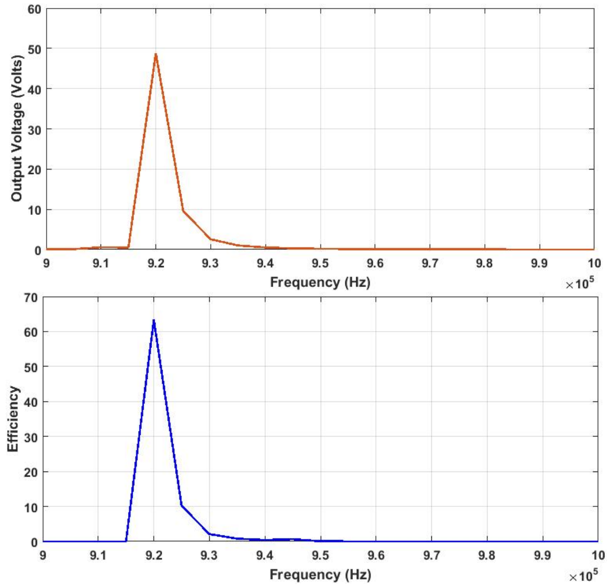



**Figure 2:** Variation of Output Voltage and Efficiency with Operating Frequency

## 3. Performance without PDM Control

To validate the proposed Maximum Energy Efficiency Tracking (MEET) strategy using Sigma Pulse Density Modulation, comprehensive simulations were conducted in MATLAB / Simulink. The primary objective was to demonstrate the effectiveness of Sigma PDM in maintaining optimal energy efficiency under varying load conditions in a wireless power transfer (WPT) system. The key performance metrics were the output voltage and the energy efficiency (η) which is the ratio of the output power to the input power. The simulation scenario consisted of fixed coupling, varying load which models the change in receiver consumption. To this end, the load resistance was varied stepwise from 20 Ω to 180 Ω in steps of 40 Ω. Without sigma delta modulation, the voltage and efficiency variation is shown in Figure 3. The efficiency increases from 52% to a maximum of 65% and then drops to around 47%. The output voltage on the other hand increases from 32 V to nearly 50 V over the range.

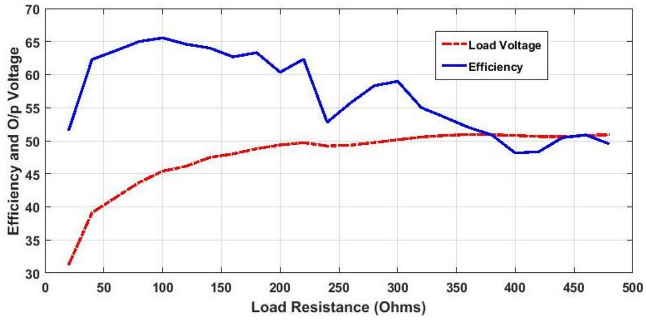



**Figure 3:** Variation of Output Voltage and Efficiency with Load Resistance in case of the Uncontrolled WPT System

The performance of the WPT system also depends on the mutual inductance between the coils which is a function of the coil spacing, alignment, medium around etc. Figure 4 shows the variation of the output voltage and the efficiency as the mutual inductance varies from 0.3 µH to 1.2 µH. Both the voltage and efficiency rise initially, reach a peak value between 0.8 µH to 1.0 µH and then decrease.

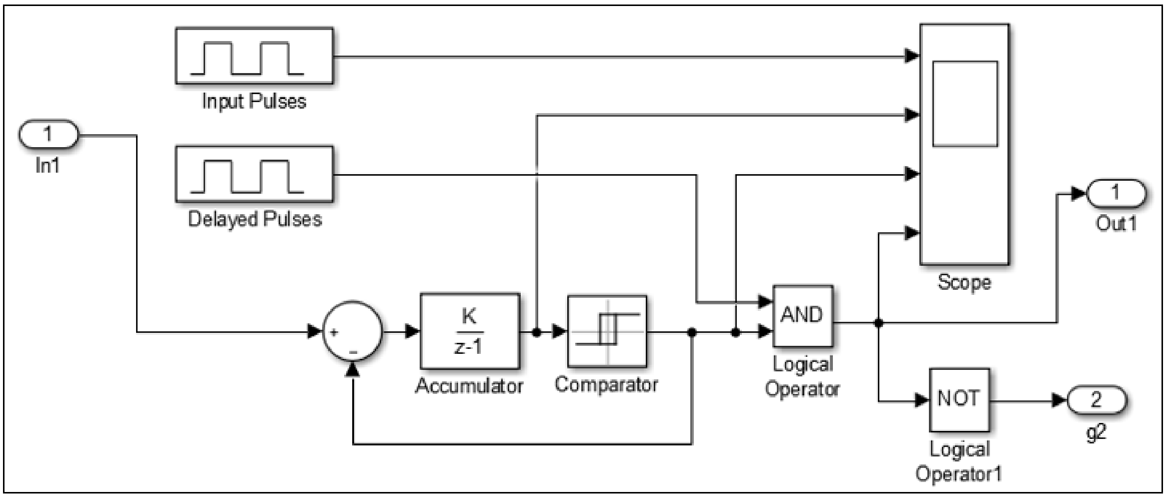
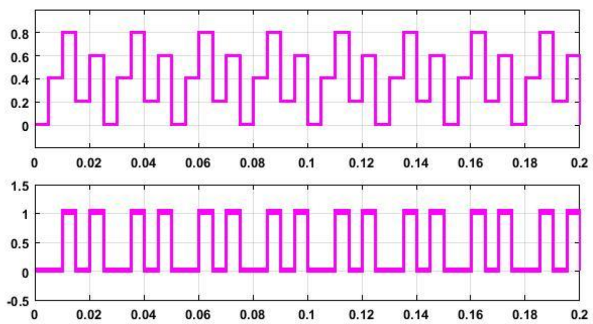
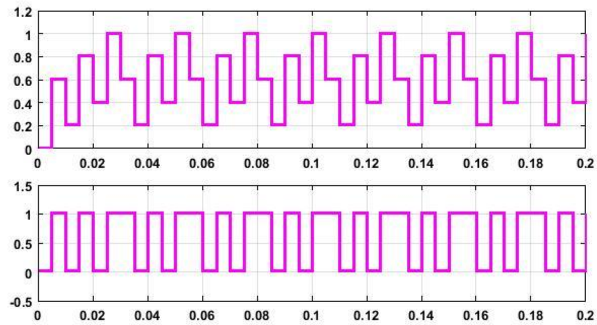



**Figure 5:** MATLAB / SIMULINK Model of the Sigma Delta Based Pulse Density Modulator

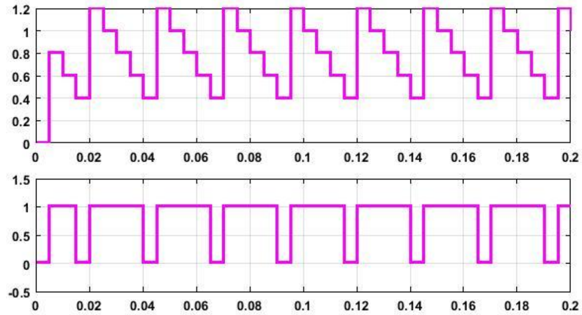


(a) d = 0.4



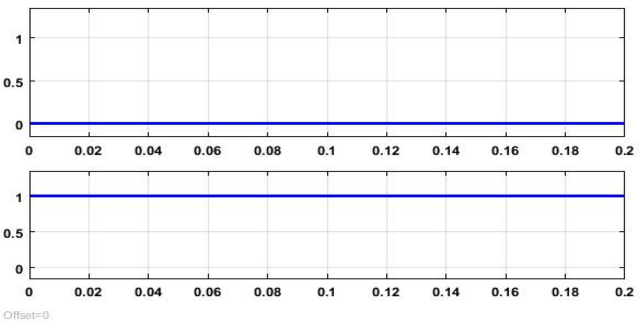
(b) d = 0.6


Paper ID: SR25829134827 DOI: https://dx.doi.org/10.21275/SR25829134827

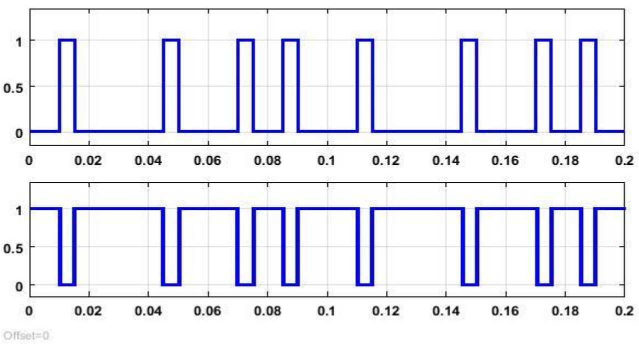


(c) d = 0.8

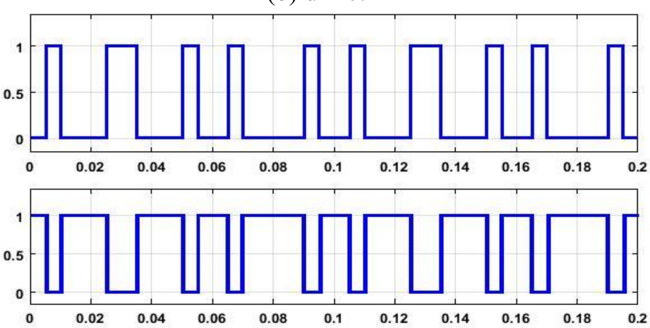
**Figure 6:** Accumulator and Comparator Outputs for (a) d = 0.4, (b) d = 0.6, (c) d = 0.8



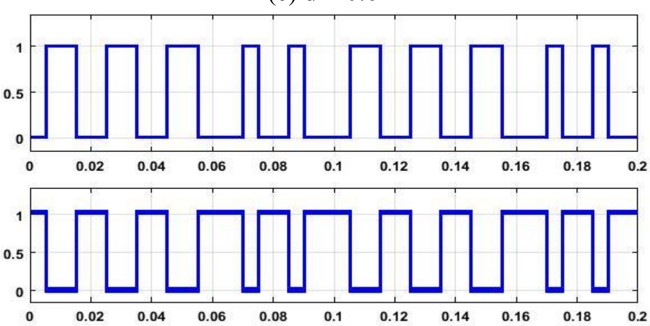
(a) d = 0



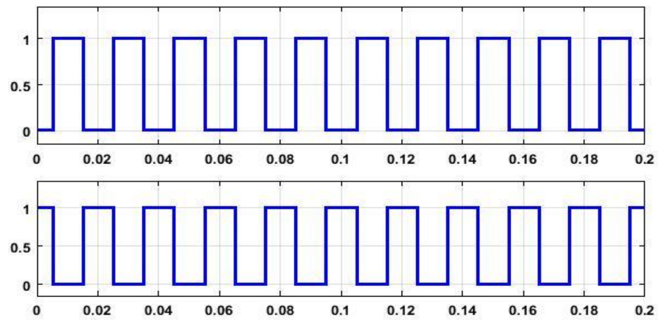
(b) d = 0.4



(c) d = 0.6



(d) d = 0.8



(e) d = 1.0

**Figure 7:** Gate pulses for (a) d= 0.2, (b) d = 0.4, (c) d = 0.6, (d) d = 0.8 and (e) d = 1.0

## 4. Performance with PDM Control

When sigma delta based pulse density modulation is employed, the results are shown in Figure 8. From the figure, it can be seen that, the over the entire load range, the efficiency can be maintained at 65% while the output voltage at 40 V. The necessary changes in the duty cycle on the transmitting and receiving side (d1 and d2) to achieve this objective is shown in Figure 2.4.

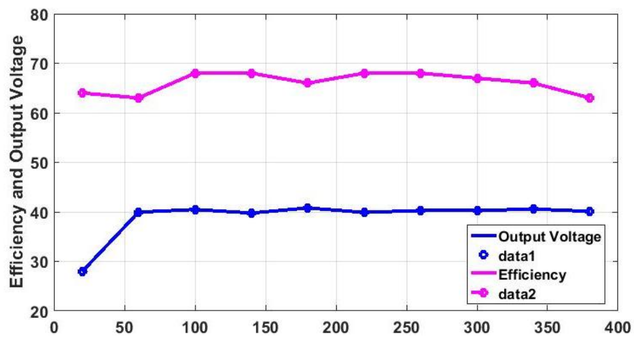



**Figure 8:** Efficiency and Output Voltage Vs Load Resistance for Sigma Delta Modulated Control

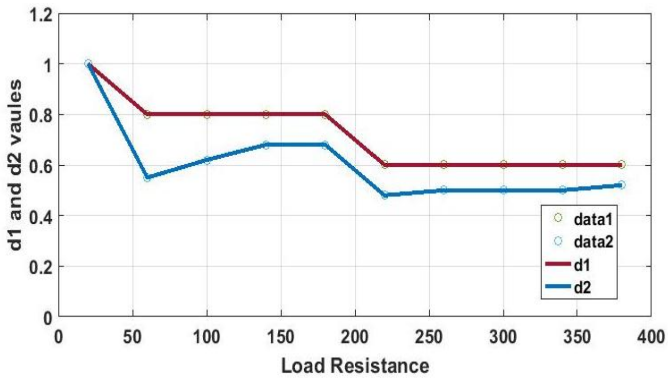



**Figure 9:** Control Parameters (Duty Cycles d1 and d2) used in maintaining constant efficiency

## 5. Conclusion

This paper presents an approach for retaining the maximum energy efficiency level over wide variations in load in a wireless power transfer (WPT) system. The efficiency tracking is achieved by means of a Sigma-Delta Modulated (SDM) controller. The Sigma-Delta form of Pulse Density Modulation enables precise control of energy transfer under varying load and coupling conditions. By suitably adjusting


Paper ID: SR25829134827 DOI: https://dx.doi.org/10.21275/SR25829134827

the switching density for a load change, the SDM controller maintains optimal operating conditions, thereby maximizing energy efficiency. Simulation results demonstrate the utility of the mechanism and its effectiveness in scenarios with fluctuating load resistance and coil misalignment. The future work aims to focus on extending this approach to multi-receiver systems and exploring hardware-in-the-loop implementations for real-time performance optimization.

## References

[1] H. Li, J. Fang, S. Chen, and Y. Tang, "Pulse Density Modulation for Maximum Efficiency Point Tracking of Wireless Power Transfer Systems," IEEE Trans. Power Electron., vol. 32, no. 11, pp. 8821–8831, Nov. 2017.

[2] W. X. Zhong and S. Y. R. Hui, "Maximum Energy Efficiency Tracking for Wireless Power Transfer Systems," IEEE Trans. Power Electron., vol. 30, no. 7, pp. 4025–4034, Jul. 2015.

[3] V. Yenil and S. Cetin, "An Improved Pulse Density Modulation Control for Secondary Side Controlled Wireless Power Transfer System Using LCC-S Compensation," IEEE Trans. Ind. Electron., vol. 69, no. 12, pp. 12762–12772, Dec. 2022.

[4] C. Wang, Y. Fan, W. Gao, K. Wang, and H. Li, "PDM-Based Feedforward Power Compensation for FMPSK Communication in WPT Systems," IEEE Trans. Circuits Syst. II: Express Briefs, vol. 69, no. 12, pp. 2241–2245, Dec. 2022.

[5] K. Unal, G. Bal, and S. Oncu, "Implementation of the Irregular Pulse Density Modulation-Controlled Wireless Power Transfer System for Constant Current and Constant Voltage Output," Int. J. Circ. Theory Appl., 2023.

[6] T. Mishima and C.-M. Lai, "Load-Adaptive Resonant Frequency-Tuned Δ–Σ Pulse Density Modulation for Class-D ZVS High-Frequency Inverter-Based Inductive Wireless Power Transfer," IEEE J. Emerg. Sel. Top. Ind. Electron., vol. 3, no. 4, pp. 411–420, 2022.

[7] W. Ye, X. Chen, and F. Liu, "Pulse Density Modulation Control to Achieve Constant Output Voltage for Multi-load Magnetically Coupled Resonant Wireless Power Transfer System," in Proc. 10th Int. Conf. Power Electron., Machines and Drives (PEMD), 2020, pp. 222–229.

[8] H. Li, S. Chen, J. Fang, Y. Tang, and M. A. de Rooij, "A Low-Subharmonic, Full-Range, and Rapid Pulse Density Modulation Strategy for ZVS Full-Bridge Converters," IEEE Trans. Power Electron., vol. 34, no. 9, pp. 8871–8881, Sept. 2019.

[9] Y. Ma, B. Liang, J. Wang, and Z. Ma, "A Novel Hill Climbing-Golden Section Search Maximum Energy Efficiency Tracking Method for Wireless Power Transfer Systems in Unmanned Underwater Vehicles," IEEE Trans. Ind. Electron., 2024.

[10] J. Zhao, L. Li, H. Wu, and L. Zhao, "An Optimized Multi-Level Control Method for Wireless Power Transfer System Using the Particle Swarm Optimization Algorithm," IEEE Trans. Power Electron., 2024.

[11] S. Patil and D. Sirico, "Maximum Efficiency Tracking in Wireless Power Transfer for Battery Charging Applications," IEEE Trans. Power Electron., vol. 30, no. 7, pp. 4025–4034, Jul. 2015.

[12] A. P. Hu, "Modeling a Contactless Power Supply Using GSSA Method," in Proc. IEEE Int. Conf. Ind. Technol., 2009, pp. 1–6.

[13] L. Q. Yuan, B. Y. Li, Y. M. Zhang, F. B. He, K. N. Chen, and Z. M. Zhao, "Maximum Efficiency Point Tracking of the Wireless Power Transfer System for the Battery Charging in Electric Vehicles," in Proc. 18th Int. Conf. Electr. Mach. Syst. (ICEMS), 2015.

[14] Y. Narusue, Y. Kawahara, and T. Asami, "Maximum Efficiency Point Tracking by Input Control for a Wireless Power Transfer System with a Switching Voltage Regulator," in Proc. IEEE Wireless Power Transfer Conf. (WPTC), 2015.

[15] B. Choi, H. Kim, and D. H. Cho, "Analysis and Design of Dual-Band Wireless Power Transfer System Based on Pulse Density Modulation," IEEE Access, vol. 8, pp. 15923–15933, 2020.

[16] M. Lee and S. Y. R. Hui, "Efficiency Optimization of Wireless Power Transfer Systems Using Load-Side Control and Maximum Efficiency Tracking," IEEE Trans. Power Electron., vol. 33, no. 6, pp. 5247–5255, Jun. 2018.

[17] Q. Tang, J. He, Y. Wu, and Z. Wang, "Research on a PDM Control Strategy for WPT Systems with Strong Coupling," Electronics, vol. 10, no. 5, p. 545, 2021.

[18] K. Park, J. Kim, and H. Kim, "Dual-Frequency Wireless Power Transfer System with PDM for Electric Vehicles," IEEE Trans. Ind. Appl., vol. 58, no. 1, pp. 439–448, Jan. 2022.

[19] Z. Liu, Y. Su, and J. Yang, "Adaptive Pulse Density Modulation Control of a Wireless Power Transfer System under Dynamic Load Conditions," IEEE Trans. Ind. Electron., vol. 70, no. 1, pp. 123–132, Jan. 2023.

[20] D. Lee, C. Lee, and J. Choi, "Digital Implementation of Pulse Density Modulation for High-Efficiency WPT," in Proc. IEEE APEC, 2019, pp. 3131–3135.