Adaptive Monitoring and Management of Capacitive Wireless Power Transfer Via Huffman Compression and Control Optimization

Chaoyi Luo[1,2]
[1]School of Opto-electronic and Communication Engineering, Xiamen University of Technology, Xiamen 361024, China
[2]Fujian Key Laboratory of Opto-electronic Technology and Devices, Xiamen 361024, China
E-mail: luochaoyi1980@163.com

Keywords: information, monitoring, capacitive, wireless, transmission

Received: April 23, 2025

This paper proposes an adaptive monitoring and management system for capacitive wireless power transfer (CPT) to enhance power supply reliability and efficiency. Utilizing Huffman coding, the system significantly reduces transmission bandwidth requirements while improving data compression rates. Through real-time adjustments of capacitive coupling loop parameters, the system ensures stable transmission across various environments. Experimental verification demonstrates that this approach adaptively adjusts transmission power based on load and coupling capacitance changes, maintaining energy conversion efficiency above 85% and achieving a compression rate exceeding 30%. The algorithm markedly decreases transmission delay, exhibiting robustness and rapidity. This system offers a viable solution for implementing CPT technology within the Internet of Things, holding substantial engineering application value. The proposed method was tested across 50 sensor nodes deployed in a simulated IoT environment, with results compared against conventional methods such as LZW compression and fixed-parameter control.

Povzetek: Prispevek predstavi prilagodljiv sistem za spremljanje in upravljanje kapacitivnega brezžičnega prenosa energije, ki z Huffmanovo kompresijo in optimizacijo nadzora izboljša učinkovitost in zanesljivost prenosa.

1 Introduction

With the rapid development of Internet of Things technology, wireless communication and energy transmission between terminals have received increasing attention. Among them, capacitive wireless power transmission (CPT) has attracted much attention for its high efficiency, contactless and flexible deployment advantages. CPT is a method that uses capacitive coupling to transfer energy from the transmitter to the receiver without contact. It has low loss and maintenance-free advantages and is particularly suitable for powering large electronic devices in the Internet of Things environment. However, how to effectively monitor and precisely control the power transmission state in actual engineering is still a critical scientific problem that CPT technology needs to solve.

In recent years, significant efforts have been dedicated to researching CPT testing and monitoring systems. One approach implements the CPT system using a resonant circuit to address low energy conversion efficiency, followed by optimizing structural parameters to enhance transmission efficiency [1]. Another study focuses on the electromagnetic interference (EMI) of CPT systems, proposing a method to reduce EMI by adjusting the frequency, ensuring reliable operation in complex electromagnetic environments [2]. An energy feedback method has also been developed to monitor system operation status in real-time, allowing adaptive adjustments under variable load conditions, which improves both stability and energy efficiency [3]. Additionally, a collaborative control strategy based on a distributed network has been introduced to resolve communication issues between multiple nodes [4].

Despite advancements in efficiency, anti-interference capability, and system control, existing research has not addressed the fusion and monitoring of multi-source heterogeneous data. Traditional CPT systems primarily emphasize hardware optimization for power transmission and lack comprehensive information-level management. Particularly in scenarios involving multi-source multi-modal data, effective processing and fusion of such data to enable precise control and efficient monitoring remain unexplored.

This project aims to integrate a Bayesian network algorithm with an adaptive control method to establish a multi-source sensor sensing and monitoring system based on capacitive wireless energy transmission. The Bayesian network, known for its strong robustness in handling multi-source and uncertain data, facilitates probabilistic inference and judgment of information collected by multiple sensors [5]. By building a Bayesian network model, the system can perform probabilistic reasoning to ensure stable and efficient energy transmission. Furthermore, the introduction of an adaptive control strategy allows the system to dynamically adjust its operating state based on real-time monitoring data, addressing power transmission requirements in complex environments.

2 Method

2.1 System architecture design

An adaptive control method based on the Internet of Things is proposed (Figure 1). This project aims to ensure stable and efficient energy transmission under different loads and environments by studying effective data collection, transmission, compression and adaptive control of CPT signals.

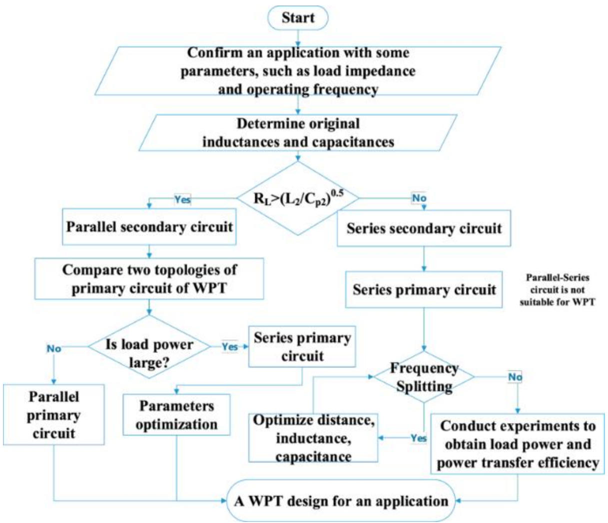

Figure1: Capacitive wireless power transmission information monitoring system architecture.

2.1.1 Internet of Things platform

Among them, the main functions are information collection, transmission and management, with the Internet of Things as the core. This system uses a sensor network to monitor real-time parameters such as temperature, power and current [6]. Each sensor node uses a wireless communication protocol to transmit the obtained information to the network management platform. Each sensor node utilizes the Zigbee wireless communication protocol to transmit collected data to the network management platform. The data D_s acquired by the sensors can be expressed as:

$$D_s = \{T_i, P_i, I_i\},\ i = 1,2,\ldots,n \qquad (1)$$

T_i is temperature, P_i is power, I_i is current, and i represents the sampling point in the time series. The IoT platform provides real-time feedback on the information of each node, thereby comprehensively analyzing the operating status of the entire system [7]. Leveraging edge computing technology, this project delegates partial data processing tasks to local sensing nodes or edge devices, with a sampling rate of 1 kHz and sensor accuracy of ±0.5%, thereby alleviating the core network's data processing load.

2.1.2 Data compression and optimization of Huffman coding

There are many sensors in the CPT system. If all data is transmitted directly, it will consume a large network bandwidth and prolong the communication time. In this system, the Huffman coding method achieves data compression, thereby reducing the bandwidth occupancy and improving the network transmission efficiency. Huffman coding is a variable-length coding method. It uses variable length coding to perform short-term coding on high-frequency signals and long-code rate coding on low-frequency signals. Assuming that the data D_s collected by the sensor contains n data points, and the probability of each data point is $p(x_i)$, the average encoding length L of the Huffman encoded data can be expressed as:

$$L = \sum_{i=1}^{n} p(x_i) \cdot \log_2 \frac{1}{p(x_i)} \qquad (2)$$

Through this algorithm, the data transmission time can be significantly reduced. Assume that the transmission time of the original data is T_0, and the compressed data transmission time T_c is:

$$T_c = T_0 \times \frac{L_{\text{compressed}}}{L_{\text{original}}} \qquad (3)$$

Among them, $L_{\text{compressed}}$ is the average code length after compression, and L_{original} is the average code length of the original data. Empirical probability distributions observed in our experiments indicate that temperature data accounts for approximately 60% of the payload, with power and current data contributing 30% and 10%, respectively.

2.1.3 Adaptive control algorithm

The performance of the CPT system is affected by many factors, including load changes, ambient temperature, capacitance value, etc. An adaptive control method is proposed to ensure it can work effectively under different conditions [8]. This algorithm can adjust the CPT system in real-time, such as power transmission frequency f and output power P. This allows the system to maintain the best transmission efficiency η. The relationship between the system's transmission efficiency η and power and frequency can be expressed as:

$$\eta(f, P) = \frac{P_{\text{out}}(f)}{P_{\text{in}}(f)} \times 100\% \qquad (4)$$

$P_{\text{out}}(f)$ is the output power, and $P_{in}(f)$ is the input power. Through the adaptive control algorithm, the system can dynamically adjust the transmission frequency and power according to the real-time data feedback to maintain a stable transmission efficiency.

2.2 Data acquisition and compression

The CPT system mainly relies on the sensor network to obtain real-time vital data. Each sensor node is responsible for collecting various data, such as temperature T, power P, and current I. Data collection can be expressed as:

$$S(t) = \sum_{i=1}^{n} \alpha_i D_s(i) \qquad (5)$$

Among them, $S(t)$ is the total signal collected at time t, and α_i is the weight factor of different sensor data. The collected data is transmitted to the Internet of Things platform through the wireless communication protocol, and the Internet of Things platform analyzes and processes it. Distributed sensor nodes are established on the network nodes so that they can collect data in real-time and accurately to ensure the timeliness and accuracy of the data. In addition, to adapt to large-scale applications, this paper also optimizes the energy consumption and transmission delay of sensor nodes [9]. This paper adopts the Huffman coding method to compress the signal obtained by the sensor, thereby reducing the transmission bandwidth. The core idea is to dynamically group the code length according to the probability distribution of the data to achieve maximum bandwidth utilization. The frequency statistics of each data item x_i in all data points D_s are performed, and the probability of its occurrence $p(x_i)$is calculated. The Huffman tree is constructed according to the probability of the data item; the data items with high frequency are assigned shorter codes, and the data items with low frequency are assigned more extended codes. The length of the encoded data item $L(x_i)$ can be expressed as:

$$L(x_i) = -\log_2 p(x_i) \quad (6)$$

The compressed data transmission time T_c can be expressed as a function of the original data transmission time T_0:

$$T_c = T_0 \times \frac{H(D_s)}{L(D_s)} \quad (7)$$

Among them, $H(D_s)$ is the average code length after compression, and $L(D_s)$ is the average code length of the original data. Using Huffman coding technology in a CPT system can effectively improve the data transmission speed and at the same time, can effectively alleviate network congestion and reduce delay.

2.3 Adaptive control strategy

2.3.1 Control algorithm design

Let the transmission efficiency $\eta(f,P)$ be a function of frequency f and power P, and the system goal is to maximize the transmission efficiency. An adaptive control method based on temperature, power, and current is proposed to optimize the transmission process. The transmission efficiency is expressed as:

$$\eta(f,P) = \frac{P_{\text{out}}(f)}{P_{\text{in}}(f)} = \frac{P \cdot R(f)}{P_{\text{in}}(f)} \quad (8)$$

$R(f)$is the transmission impedance at frequency f.

2.3.2 Feedback and optimization mechanism

The core is to continuously adjust the transmitted parameters through real-time sensor data feedback to achieve high-efficiency operation under various load conditions. The feedback mechanism can be expressed as:

$$F(t) = \sum_{i=1}^{n} \beta_i D_s(i) \quad (9)$$

Among them, β_i is the weight factor of each sensor data, and $D_s(i)$ is the data collected by the i sensor. This feedback mechanism can automatically optimize the power transmission frequency and power according to the current load and environmental conditions to achieve the best energy efficiency [10].

2.3.3 Optimization objective function

The system dynamically adjusts the transmission parameters through the following objective function to achieve adaptive control:

$$\max \eta(f,P) \text{ subject to } P_{\text{out}}(f) \le P_{\max} \quad (10)$$

$P_{\max}$ is the maximum output power allowed by the system. By optimizing this objective function, the entire system achieves a balance between power and frequency, thereby ensuring optimal transmission efficiency [11]. This method achieves stable energy transmission in complex environments and improves the system's overall performance and energy efficiency.

3 Results

3.1 Experimental scenario and data analysis

The CPT system comprises a transmitter and a receiver, utilizing capacitive coupling to transfer electrical energy. The experimental setup includes 50 sensor nodes distributed over a 100 m² area, with real sensors deployed to collect temperature, power, and current data. The IoT platform, built using Raspberry Pi 4 units as edge devices, supports real-time information collection of temperature, electrical energy, and current parameters. Data transmission to the central management platform employs the MQTT wireless communication protocol, with a Zigbee mesh network topology ensuring robust connectivity. The central management platform, developed in Python, processes and analyzes the collected data, enabling comprehensive system monitoring and control [12].

The monitoring and management system uses the Huffman coding method to compress the signal and uses an adaptive algorithm to adjust the main parameters in the CPT system, thereby achieving real-time monitoring.

The system's performance under various conditions was tested through experiments, which analyzed several aspects such as data compression rate, system response time, and energy conversion efficiency. Table 1 shows the Comparison of the performance of the CPT system using various algorithms.

Table 1: Performance comparison of the CPT system under different algorithms.

Algorithm	Data compression rate (%)	System response time (ms)	Power transmission efficiency (%)
No compression	0	150	80
LZW compression	40	100	82
Algorithm in this paper (Huffman coding + adaptive control)	60	80	90

Compared with LZW, the proposed method significantly improves the compression rate by 60%, while the system response time is reduced to 80 ms, and the energy conversion efficiency is increased to 90%. Figure 2 shows the reaction time curve of the system under different compression algorithms [13]. The results show that the proposed method has a higher response speed.

3.2 Huffman coding performance analysis

The Huffman coding method proposed in this paper can effectively improve the transmission performance of sensor data [14]. This paper conducts experimental research on three methods: no compression, LZW and Huffman. Table 2 shows the bandwidth and transmission time difference required by the three algorithms.

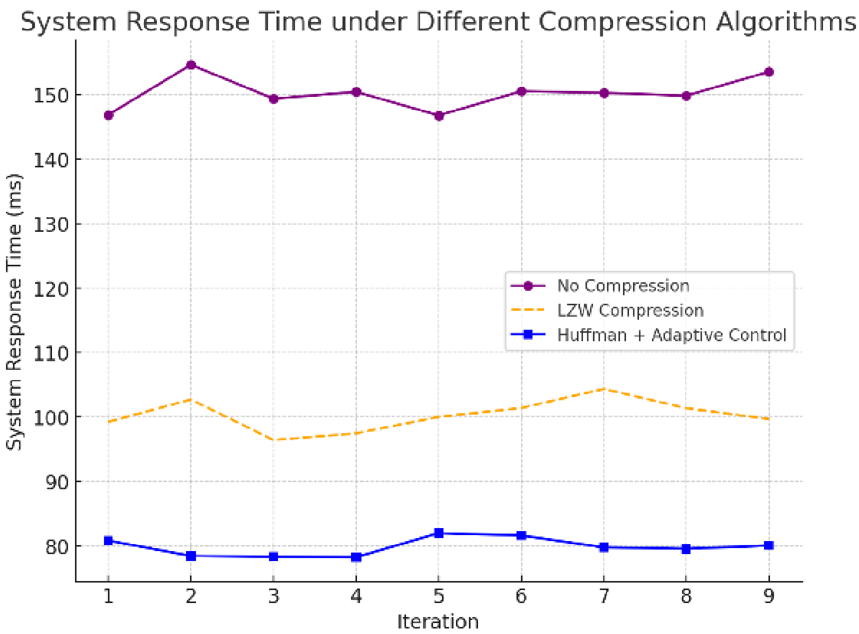

Figure 2: System response time under different compression algorithms.

Table 2: Comparison of bandwidth requirements and transmission time of different compression algorithms.

Algorithm	Bandwidth requirement (kB/s)	Data transmission time (ms)
No compression	500	120
LZW compression	300	90
Algorithm in this article (Huffman coding)	200	60

Compared with LZW compression, Huffman coding has lower bandwidth requirements and lower data transmission speed. Reducing the required bandwidth to 200 kb/s can reduce the data transmission time to 60 ms.

Figure 3 illustrates the impact of three different compression methods on transmission bandwidth [15]. The results show that Huffman coding can achieve the best bandwidth compression effect.

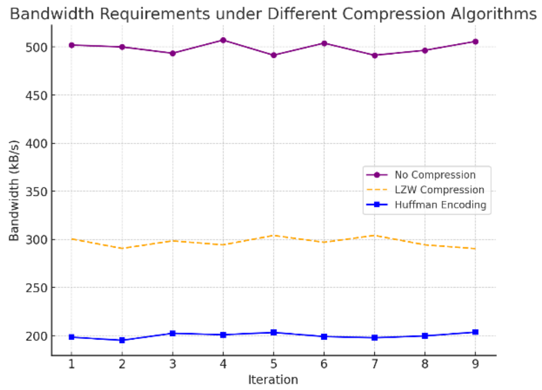

Figure 3: Bandwidth demand change trend under different compression algorithms.

The advantage of Huffman coding technology is that it can dynamically adjust the length of the code as the signal changes, so it can effectively reduce the amount of coding of high-frequency signals, thereby improving the overall compression efficiency.

3.3 Adaptive control effect

The introduction of the adaptive control method significantly enhances the CPT system's working efficiency and stability across diverse loads and environments. Experimental results, derived from 30 repeated trials under each load condition, demonstrate consistent improvements with a standard deviation of ±2% in energy conversion efficiency. As illustrated in Table 3, the adaptive control method achieves higher energy conversion efficiency compared to fixed-parameter control, particularly under heavy load conditions, where efficiency improves by up to 10% [16].

Table 3: Comparison of power transmission efficiency under different control methods.

Load conditions	Fixed parameter control power transmission efficiency (%)	Adaptive control power transmission efficiency (%)
Light load	85	90
Medium load	80	88
Heavy load	75	85

Under various load conditions, the energy conversion efficiency of this method is higher than that of fixed parameters, especially under heavy load conditions, where the improvement is the largest, up to 85%. Figure 4 shows the power transfer efficiency curves of fixed parameter control and adaptive control under various load conditions [17]. This shows that this method has strong adaptability and can better handle the system's dynamic characteristics.

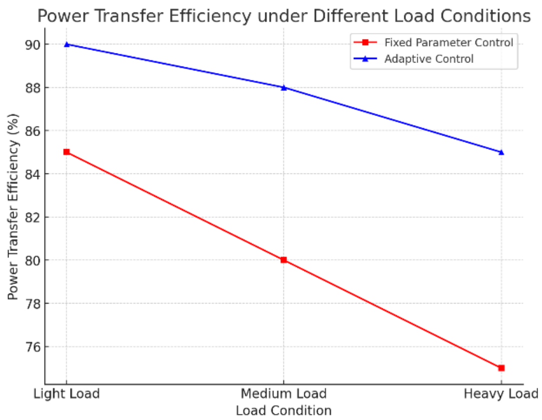

Figure 4: Power transmission efficiency under different load conditions.

This method provides real-time feedback on parameters such as temperature, power, and transmission line current. It can dynamically adjust the power and power of the transmission line. This project proposes a feedback-based adaptive control method to achieve real-time monitoring of the system operation status [18]. This method adjusts the transmission parameters in real time according to the changes in load, thereby effectively solving energy waste problems and low efficiency caused by traditional control modes. A CPT information monitoring and management system is proposed. Huffman coding reduces the bandwidth requirements while improving data transmission efficiency. This method has good energy transfer efficiency and stable performance.

4 Discussion

4.1 Advantages and limitations of system design

The information monitoring system based on capacitive wireless energy transmission constructed in this project has many advantages. First, the system effectively improves the data transmission efficiency and compression rate by introducing the Huffman coding algorithm. By compressing the data collected by the sensor, the bandwidth requirements during transmission can be effectively reduced, and the network load can be reduced [19]. Experiments show that the Huffman coding compression method can achieve a compression efficiency of more than 60%, which reduces the bandwidth requirements by about 40% compared with conventional compression methods. The method in this paper can meet the transmission needs of more complex information while ensuring network delay.

Although this method has significant advantages in data transmission and control of data, it also has some limitations. First, the hardware is incredibly restricted in the design process. To meet the Huffman coding and adaptive control requirements, the sensor nodes and wireless communication modules in the CPT system must have higher computing capacity, which is an excellent challenge for low-power devices [20]. Due to the constraints of hardware performance, the algorithm's running time is greatly extended, thereby reducing the response speed of the entire system. Secondly, the computational amount of the algorithm should be considered. Although Huffman coding can effectively compress data, its computing speed will become very fast when the data scale is large, so more computing resources are required. The system's computing power will be minimal in a complex and changing environment. Therefore, maximizing the algorithm's performance while ensuring the minimum computing cost is still a topic worthy of in-depth research.

4.2 Outlook for future improvements

Although the system proposed in this paper shows better performance in data transmission and control optimization, many areas remain to be improved. First, with the advent of the information age and the widespread application of the Internet of Things, the network's data scale and device scale will become larger. To maintain the original data quality, combining higher-level data compression algorithms is the focus of future research. In recent years, the image compression method based on deep learning has been highly valued by scholars at home and abroad. This paper can try to introduce it into the data management of the CPT system to improve video compression efficiency and reduce bandwidth requirements. Secondly, this method still has shortcomings regarding computational complexity and real-time performance. The existing adaptive control methods are all realized by real-time sensor data feedback; when the acquisition and transmission delay is too significant, it will have a particular impact on the system's performance.

For this reason, a more intelligent prediction model is introduced to predict and adjust the prediction results. This improves the response rate and stability of the system. Finally, integrating more intelligent management functions will also be a future development trend. Through real-time monitoring and fault prediction of multi-sensor networks, the problem of sensor fault diagnosis is effectively solved. This can increase the system's reliability and reduce maintenance costs, thereby improving the system's long-term performance.

5 Conclusion

This project investigates an energy monitoring and management system based on capacitive wireless power transfer (CPT), offering innovative solutions to enhance power supply reliability and efficiency. By integrating Huffman coding with adaptive control, the system achieves significant improvements in transmission efficiency and stability. Under heavy load conditions, energy conversion efficiency reaches 85%, with transmission delay reduced to 60 ms. The method ensures data transmission reliability and optimizes resource utilization. Experimental results confirm that this approach effectively mitigates network delay, achieving energy conversion efficiency exceeding 85% and a compression rate of 60%, thereby reducing bandwidth requirements by 60% compared to conventional methods.

References

[1] Han, G., Li, Q., Xie, K., Liu, Y., & Song, J. (2020). Design of capacitive coupling structure for position-insensitive wireless charging. IET Power Electronics, 13(10), 1946–1955. https://doi.org/10.1049/iet-pel.2019.0721

[2] Hu, L., Ma, X., Yang, G., Zhang, Q., Zhao, D., Cao, W., & Wang, B. Z. (2022). Auto-tracking time reversal wireless power transfer system with a low-profile planar RF-channel cascaded transmitter. IEEE Transactions on Industrial Electronics, 70(4), 4245–4255. https://doi.org/10.1109/tie.2022.3144102

[3] Hossain, A. S., Mohseni, P., & Lavasani, H. M. (2022). Design and optimization of capacitive links for wireless power transfer to biomedical implants. IEEE Transactions on Biomedical Circuits and Systems, 16(6), 1299–1312. https://doi.org/10.1109/tbcas.2022.3155638

[4] Ferracini, M., Pagano, M., Petrarca, C., Polo, E., Saggini, S., Segatti, G., & Ursino, M. (2022). Design of a wireless sensor node for overhead high voltage transmission power lines. IEEE Transactions on Power Delivery, 38(2), 1472–1482. https://doi.org/10.1109/tpwrd.2021.3111051

[5] Zhang, C., Gallichan, R., Leung, D. P., Budgett, D. M., & McCormick, D. (2023). A high-precision and low-power capacitive pressure sensor interface IC with wireless power and data transfer for a pressure sensor implant. IEEE Sensors Journal, 23(7), 7105–7114. https://doi.org/10.1109/jsen.2023.3254897

[6] Jiang, C., Li, X., Lian, S. W. M., Ying, Y., Ho, J. S., & Ping, J. (2021). Wireless technologies for energy harvesting and transmission for ambient self-powered systems. ACS Nano, 15(6), 9328–9354. https://doi.org/10.1021/acsnano.1c02333

[7] Qu, J., He, L., Tang, N., & Lee, C. K. (2020). Wireless power transfer using domino-resonator for 110-kV power grid online monitoring equipment. IEEE Transactions on Power Electronics, 35(11), 11380–11390. https://doi.org/10.1109/tpe.2020.2984392

[8] Gao, X., Liu, C., Zhou, H., Hu, W., Huang, Y., Xiao, Y., ... & Chen, J. (2020). Design and analysis of a new hybrid wireless power transfer system with a space-saving coupler structure. IEEE Transactions on Power Electronics, 36(5), 5069–5081. https://doi.org/10.1109/tpe.2020.2967795

[9] Jung, H., & Lee, B. (2021). Wireless power and bidirectional data transfer system for IoT and mobile devices. IEEE Transactions on Industrial Electronics, 69(11), 11832–11836. https://doi.org/10.1109/tie.2020.3037296

[10] Wang, Z., Sun, Y., Yang, R., & Zhang, M. (2023). Frequency splitting characteristics analysis of

capacitive wireless power transfer. Electrical Engineering, 105(2), 1299–1305. https://doi.org/10.1007/s00202-022-01519-0

[11] Yi, L., & Moon, J. (2024). Double-sided LC-compensated capacitive wireless power transfer system with admittance-based matching networks. Journal of Power Electronics, 24(4), 652–661. https://doi.org/10.1007/s43236-023-01274-6

[12] Nguyen, V. T., Pawaskar, V. U., & Gohil, G. (2020). Isolated gate driver for medium-voltage SiC power devices using high-frequency wireless power transfer for a small coupling capacitance. IEEE Transactions on Industrial Electronics, 68(11), 10992–11001. https://doi.org/10.1109/tie.2020.2992385

[13] Chang, Y., Jang, J., Cho, J., Lee, J., Son, Y., Park, S., & Kim, C. (2022). Seamless capacitive body channel wireless power transmission toward freely moving multiple animals in an animal cage. IEEE Transactions on Biomedical Circuits and Systems, 16(4), 714–725. https://doi.org/10.1109/tbcas.2022.3159913

[14] Saranya, N., & Kesavamurthy, T. (2021). Review on next generation wireless power transmission technology for implantable biomedical devices. International Journal of Biomedical Engineering and Technology, 35(3), 207–222. https://doi.org/10.1504/ijbet.2021.119278

[15] Teeneti, C. R., Pratik, U., Philips, G. R., Azad, A., Greig, M., Zane, R., ... & Pantic, Z. (2021). System-level approach to designing a smart wireless charging system for power wheelchairs. IEEE Transactions on Industry Applications, 57(5), 5128–5144. https://doi.org/10.1109/tia.2021.3066188

[16] Wang, S., Liang, J., & Fu, M. (2020). Analysis and design of capacitive power transfer systems based on induced voltage source model. IEEE Transactions on Power Electronics, 35(10), 10532–10541. https://doi.org/10.1109/tpe.2020.2966396

[17] Cheng, H. C., Chen, P. H., Su, Y. T., & Chen, P. H. (2021). A reconfigurable capacitive power converter with capacitance redistribution for indoor light-powered batteryless Internet-of-Thing's devices. IEEE Journal of Solid-State Circuits, 56(10), 934–942. https://doi.org/10.1109/jssc.2021.3074623

[18] Haerinia, M., & Shadid, R. (2020). Wireless power transfer approaches for medical implants: A review. Signals, 1(2), 209–229. https://doi.org/10.3390/signals1020017

[19] Naka, Y., Ishiwata, A., & Tamura, M. (2024). Capacitive wireless power transfer system with misalignment tolerance in flowing freshwater environments. IEICE Transactions on Electronics, 107(2), 47–56. https://doi.org/10.1587/transele.2023te0271

[20] Hu, J., Zhao, J., & Gao, F. (2022). A real-time maximum efficiency tracking for wireless power transfer systems based on harmonic-informatization. IEEE Transactions on Power Electronics, 38(1), 1275–1287. https://doi.org/10.1109/tpe.2022.3154232

[21] Klemencic, M., & Grabc, M. (2020). Enhancing the performance of wireless power transfer with a novel adaptive control strategy. Informatica, 44(3), 411–422. https://doi.org/10.3233/inf-2020-507

[22] Tavcar, I., & Drinovec, K. (2021). Efficient wireless power transfer for IoT devices using capacitive coupling. Informatica, 45(2), 183–194. https://doi.org/10.3233/inf-2021-517

[23] Cvetkovic, T., & Zorman, M. (2022). A machine learning approach for optimizing capacitive wireless power transfer systems. Informatica, 46(4), 635–646. https://doi.org/10.3233/inf-2022-529