

Article

Bidirectional Information Transmission in SWIPT System with Single Controlled Chopper Receiver

Jie Wu ^{1,2,*}, Chongyan Zhao ³, Nan Jin ^{1,2,*} , Shuaibiao He ¹ and Dianguang Ma ⁴

¹ School of Electrical and Information Engineering, Zhengzhou University of Light Industry, 5 Dongfeng RD., Zhengzhou 450002, China

² International Joint Lab for Smart Micro-Grid of Henan, 5 Dongfeng RD., Zhengzhou 450002, China

³ Henan Institute of Product Quality Supervision and Inspection, 10 Baifo South RD., Zhengzhou 450002, China

⁴ Key Laboratory of Control of Power Transmission and Transformation Ministry of Education, Shanghai Jiao Tong University, 800 Dongchuan RD., Shanghai 200240, China

* Correspondence: wujie@zzuli.edu.cn (J.W.); jinnan@zzuli.edu.cn (N.J.)

Received: 28 June 2019; Accepted: 8 September 2019; Published: 12 September 2019



Abstract: The wireless power transfer (WPT) technology has the advantages of convenience, safety and reliability due to its non-metal contact power supply and has a broad application prospect in many occasions. In practical applications, the information communication between the primary and secondary side is necessary for output voltage control, load detection, condition monitoring and other functions, which makes the WPT system more intelligent and convenient. A simultaneous wireless information and power transfer (SWIPT) system with controlled chopper circuit receiver is proposed in this paper. The load voltage remains constant by adjusting the pulse width of the secondary controlled device through feedback control. The information bidirectional transmission methods and two modes are proposed, considering different application scenarios. Simulation and experiment results validate the proposed topology and the method of information bidirectional transmission.

Keywords: simultaneous wireless information and power transfer; controlled chopper receiver; bidirectional transmission; constant load voltage

1. Introduction

Traditional power supply generally means wire transfer, which is not safe because of metal contact failure, electric spark, short circuit, and so on. Most of these failures result from metal contact. The wireless power transfer (WPT) technology employs the form of contactlessness, and supplies power to a load at a certain distance, so that the power supply mode in WPT is more flexible and safer, and the power safety problems existing in the conventional power supply mode can be avoided. Due to its advantages, the WPT technology has been applied in broad fields, such as in electronics, medical equipment, electric vehicles and other fields [1–4]. According to the mechanism of power transmission, there are two types of WPT, i.e. the far-field wireless transfer and the near-field wireless transfer [5,6].

The information, such as output voltage control, load detection, and status monitoring, can be communicated between the primary and secondary sides in the WPT system [7–11]. The WPT system with simultaneously information transfer is called SWIPT (simultaneous wireless information and power transfer) system. In practical applications, information transmission in the WPT system makes the devices more intelligent and convenient. For example, the wireless charger transfers signals to control the status of the battery, then the charger could be equipped with constant voltage or constant current characteristics, which makes the charger efficient and gives the battery a long lifetime. Another case is an implantable medical device, such as self-contained intracardiac pacemaker. As the

implantable medical device is implanted inside the body, the WPT technology makes the device more convenient to use. At the same time, the implantable medical device is able to record human health data and export data during wireless charging, and thus the monitoring of human health is more accurate and convenient.

A direct way for SWIPT is to establish an independent link by using extra coils or antennas to transmit information and power simultaneously [12]. Obviously, this method is not suitable for implantable self-contained medical devices, because the extra components lead to large implementation costs, while the microelectronics or implantable medical devices have strict limits on size and cost. Another way for SWIPT is to transfer information and power by means of modulation schemes [13]. There are currently two main methods of modulation schemes to realize SWIPT function. The first one is referred to as information carrier-based modulation. It is to build an independent information transfer channel on the basis of WPT system, and to transmit information by modulating and demodulating the information carrier [14–18]. The second one employs the power channel as a carrier for information transmission and transmits information by regulating the power carrier [19–29], so this method is referred to as power carrier-based modulation.

Wu et al. [14] developed a SWIPT system, in which the power and data transfer share the same inductive link, they are transmitted by employing different frequency carriers and controlled independently. The ferrite-core coupled inductors are used for data-carrier coupling, and they are magnetically coupled with power resonant tank too. Lee et al. [15] considered a scenario of information exchange between two IoT devices. Simple energy storage devices such as supercapacitors are necessary in this system, and the conventional SWIPT cannot be directly applied to this system. Sun et al. [17] employed four magnetically coupled inductors to transfer data bidirectional. Furthermore, two high-frequency trappers are employed to separate the power and data transfer. Therefore, it is a high order resonant system. Yu et al. [18] designed one inner circuit to realize energy and data reception, the data transmission is realized by controlling several inner switches on and off. Overall, in the information carrier-based method, the influence of information on power is small, but the information modulation and demodulation circuit greatly increases the system cost and size, and the power carrier is much larger than the information carrier, so it has a great influence on the information transmission stability.

As for the power carrier-based modulation, there are many information modulation methods used in this method, such as amplitude shift keying (ASK) [19–21], frequency shift keying (FSK) [22–24], phase shift keying (PSK) [25–27], load shift keying (LSK) [28–31], cyclic on-off keying (COOK) [32,33], and so on. The ASK is a type of amplitude modulation which represents the binary data in the form of variations in the amplitude of signal. The binary signal, when ASK is modulated, gives a small value for low input while it gives a high value for high input. The FSK is a scheme of frequency modulation in which the frequency of the carrier signal varies according to the digital signal changes. The output of an FSK modulated wave is high in frequency for a binary high input and is low in frequency for a binary low input. The binary 1s and 0s are called Mark and Space frequencies. The PSK is a digital modulation technique in which the phase of the carrier signal is changed by varying the sine and cosine inputs at a particular time. The LSK modulate the load at the secondary side by adjusting the output impedance. The COOK transmits data by shorting and opening the secondary resonant tank. The LSK and COOK are only applied in backward information transmission.

Wang et al. [19] proposed a method of SWIPT technology, considering four coils magnetically coupled resonant WPT system, which combines ASK modulation and demodulation circuit. Yilmaz et al. [20] use the power transmission circuit as the channel for information transmission; the information forward transmission is realized by FSK, but these forward information modulation methods have a great influence on power transmission. It is the common inherent feature of power carrier-based modulation, because the information transmission depends on power transfer. Mandal and Sarpeshkar [28] proposed wireless data telemetry links for implanted biomedical system. It minimizes power consumption in the implanted system by using impedance modulation to transmit

high-bandwidth information from the implanted to the external system. The information backward modulation methods require additional switching devices and driving circuits for signal modulation, which inevitably increases system cost and size. Due to the continuous switching of load, the power of the system will fluctuate and affect the power quality.

In summary, there is no perfect solution, people must carefully seek the balance of information, power, volume, cost and other factors. Due to the independent information channel, the cost and size of the system based on the information carrier modulation is much higher than that of power carrier-based modulation. The magnetic interference of information carrier-based method between power and information transfer carriers reduces the communication quality. Therefore, the power carrier-based method is more suitable for microelectronics or implantable medical devices due to its small size and low cost. This paper designs the SWIPT system using the power carrier-based method.

A SWIPT system with controlled chopper circuit receiver is proposed in this paper. There is only one extra controlled switch on the secondary side. The constant load voltage is achieved by adjusting the voltage angle of the controlled switch through feedback control. The information forward transmission is realized by changing the power transmission frequency and designing forward demodulator. The information backward transmission is realized by changing the switching frequency of the controlled chopper circuit at the secondary side and designing backward demodulator. The predefined instruction mode and continuous data transmission mode are proposed for different working conditions, which makes the information transmission more flexible and convenient.

This paper is organized as follows. Section 2 shows the model of proposed structure, analyzes the principle of power transfer and constant voltage output control strategy. Section 3 elaborates the principles of information forward and backward transmission. Section 4 presents the modulation of bidirectional information transmission and control algorithm of simultaneous power and information transfer. In Section 5, simulation and experiments validate the proposed topology and bidirectional information transmission methods. Finally, Section 6 draws the conclusion.

2. Model and Analysis of the Proposed SWIPT System

2.1. Model of the Proposed Topology

The schematic diagram of the proposed SWIPT system is shown in Figure 1, V_{in} is the input voltage source, and the $Q_1 \sim Q_4$ constitute the active bridge at the primary side. The controllable switch Q_5 and diode D_5 are connected between the bridge rectifiers and the load at the secondary side, the switch Q_5 implements chopper control at the secondary side. The L_1 , L_2 , C_1 , C_2 , R_1 , and R_2 are the coil inductance, compensation capacitance and resistance, respectively; the subscript 1 and 2 denote the primary and secondary side. R_L is the load resistance, V_o is the load voltage. The capacitance C_o keeps load voltage stable. R_e is the equivalent load of the secondary side.

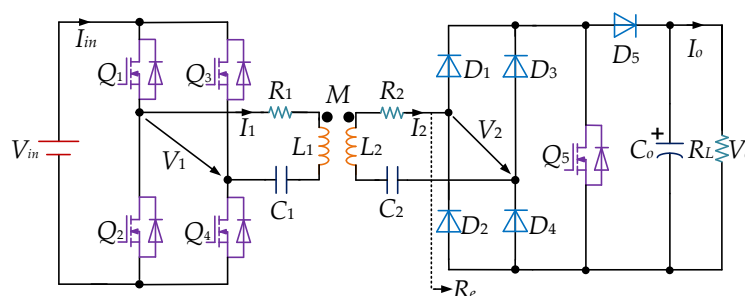


Figure 1. Schematic diagram of proposed simultaneous wireless information and power transfer (SWIPT) structure with controlled chopper receiver.

The WPT system is powered by a DC voltage source, and high frequency AC voltage is generated from the primary active bridge [5,6], which converts the power to a time-varying electromagnetic

field. The primary and the secondary coils transmit power through electromagnetic induction. The secondary coil picks up the power and converts it back to DC by the bridge rectifier, then the DC current flows through the load. Finally, the power is transferred wirelessly from the primary to the secondary side. The L_1 , C_1 and L_2 , C_2 couple in series and form resonant tank to counteract the reactive power and to improve the power factor.

The power frequency is the same as the resonant frequency of compensation circuits at the primary and secondary sides, so the resonant compensation circuits of both sides are resistive.

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

According to Kirchhoff's voltage law, the circuit is expressed as

$$R_1 I_1 - j\omega M I_2 = V_1 \quad (2)$$

$$j\omega M I_1 = V_2 + R_2 I_2 \quad (3)$$

2.2. Analysis of Wireless Power Transfer

The typical waveforms of transmitter and receiver are shown in Figure 2, where the blue line indicates voltage, the carmine dotted line is current, 2α and 2β present the voltage angle of V_1 and V_2 , respectively. The frequency of Q_5 is two times the power frequency, and the voltage angle of V_2 is regulated by controlling the pulse width γ . Due to resonance, the primary and secondary circuits are resistive, i.e. V_1 and I_1 , V_2 and I_2 are in phase, and V_2 leads V_1 90° degrees. The relationship between α , γ and the load voltage V_o is obtained through the following analysis.

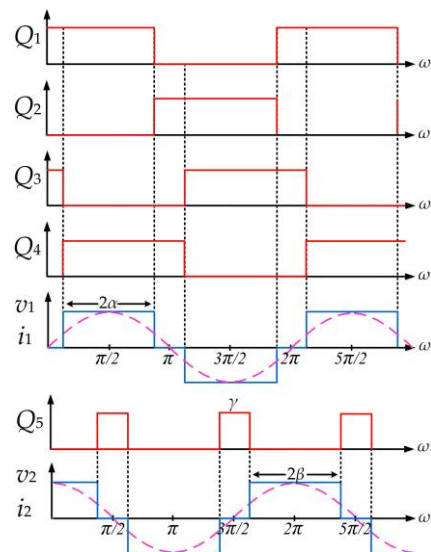


Figure 2. Typical waveforms of transmitter and receiver.

According to the Fourier series and harmonic analysis, the fundamental RMS value of the secondary voltage V_2 is denoted as

$$V_2 = \frac{2\sqrt{2}}{\pi} V_o \sin \frac{\pi - \gamma}{2} \quad (4)$$

Neglecting the losses of the switches, there be formula as follow

$$V_2^2 / R_e = V_o^2 / R_L \quad (5)$$

Combining the formulas (4) and (5), the relationship between the secondary equivalent resistance R_e and the voltage angle of Q_5 is as follows

$$R_e = \frac{8}{\pi^2} R_L \sin^2 \frac{\pi - \gamma}{2} \quad (6)$$

The reflected impedance of the secondary to the primary side can be expressed as

$$Z_r = \frac{\omega^2 M^2}{R_2 + R_e} \quad (7)$$

The currents of the primary and secondary sides, i.e. I_1 and I_2 are expressed as

$$I_1 = \frac{V_1}{R_1 + Z_r} = \frac{(R_e + R_2) V_1}{R_1 (R_e + R_2) + \omega^2 M^2} \quad (8)$$

$$I_2 = \frac{j\omega M I_1}{R_e + R_2} = \frac{j\omega M V_1}{R_1 (R_e + R_2) + \omega^2 M^2} \quad (9)$$

Equivalent resistance voltage of the secondary side is $V_2 = R_e I_2$. Combining with formula (9), the following formula holds,

$$V_2 = \frac{j\omega M I_1 R_e}{R_e + R_2} = \frac{j\omega M R_e V_1}{R_1 (R_e + R_2) + \omega^2 M^2} \quad (10)$$

Substituting (4) and (6) into (10), the load voltage V_o is obtained.

$$V_o = \frac{2\sqrt{2}\pi\omega M R_L V_1 \sin[(\pi - \gamma)/2]}{\pi^2 \omega^2 M^2 + \pi^2 R_1 R_2 + 8 R_1 R_L \sin^2[(\pi - \gamma)/2]} \quad (11)$$

Obviously, the load voltage V_o is related to the pulse width γ . The load voltage can be regulated by controlling the angle γ with the specific system parameters. The control structure for constant voltage output with single switch receiver is shown in Figure 3. The output load voltage is sampled and compared with the reference voltage U^* . The PID control is adopted to keep load voltage stable during power and information transmission.

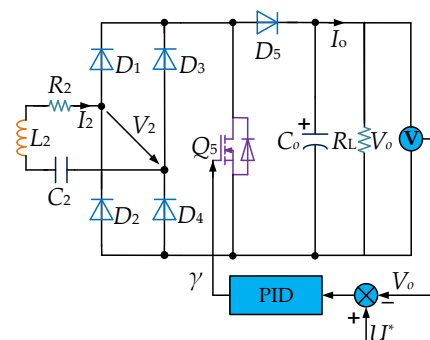


Figure 3. Control structure at the secondary side.

3. Principle of Information Transmission

3.1. Information Forward Transmission

The structure of information forward transmission is shown in Figure 4. The DSP controller of primary side generates PWM signals to drive the converter, then produces high frequency AC power that is received by the secondary side. The frequency of the resonant capacitor voltage at the secondary side is consistent with the AC power frequency, that is, the resonant capacitor C_2 and the primary PWM

signals are provided with the same frequency. The voltage waveforms of different power frequencies are shown in Figure 5.

The forward information is demodulated from the resonant capacitor C_2 , as shown in Figure 4. The voltage signal is reduced by the divider resistances R_3 and R_4 ; D_0 is the transient voltage suppressor used to limit the voltage. The rectangular wave signals with the same frequency as the PWM signals of inverter are obtained by a comparator A_1 .

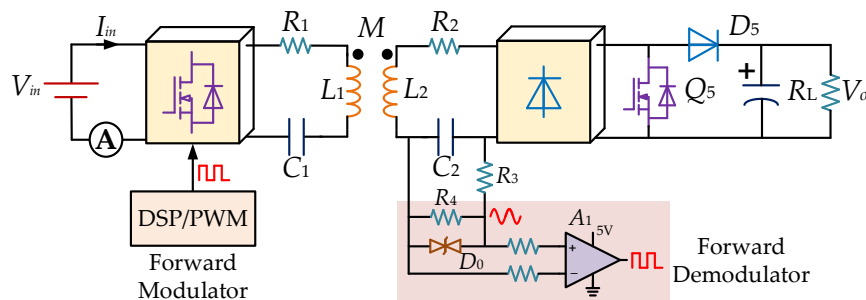


Figure 4. Structure diagram of information forward transmission.

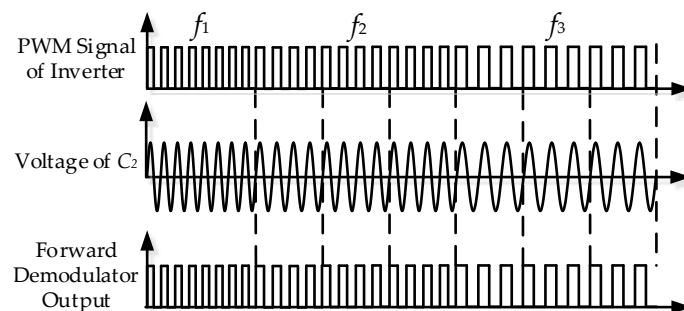


Figure 5. Voltage waveforms of different power frequencies.

In this paper, 85 kHz is selected as the primary side resonance frequency, when the information is forward transmitted; thus, 85 kHz and another frequency are required to represent the 1 and 0 signals, respectively. The second frequency cannot differ greatly from the resonant frequency 85 kHz, otherwise the resonant compensation circuit generates a large amount of reactive power, and the efficiency decreases. Moreover, if the difference between the second frequency and the resonant frequency 85 kHz is too small, the DSP cannot distinguish them, then the signal demodulation could be failed. Therefore, the second frequency needs careful consideration.

3.2. Information Backward Transmission

When the frequency of Q_5 is lower than the power frequency, the feedback control of the secondary side is adopted to keep the load voltage stable. If the Q_5 is turned off, the system load is R_L , the transmission power is at a high level; if the Q_5 is turned on, the load is shorted, the transmission power is reduced. Due to the power change of system caused by Q_5 turn-on and turn-off in the low frequency state, the input current I_{in} also changes at the same frequency as that of Q_5 . Therefore, the backward information could be demodulated from the input current I_{in} . The structure diagram of information backward transmission is shown in Figure 6.

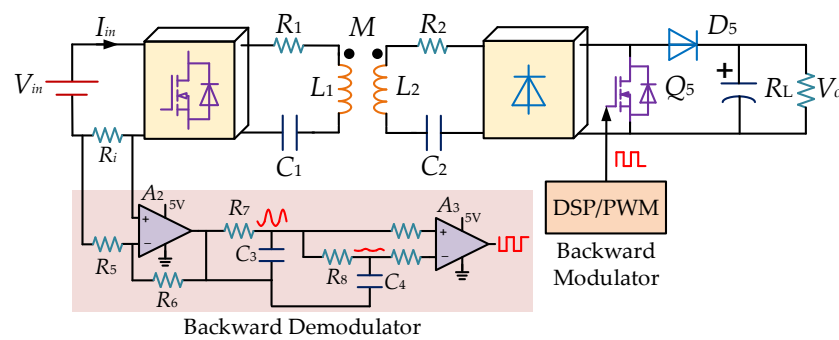


Figure 6. Structure diagram of information backward transmission.

As shown in Figures 6 and 7, the sampling resistance R_i and DC voltage source are connected in series in order to sample the input current. Since R_i is small, an amplifier consisting of R_5 , R_6 and A_2 is used to amplify the signal. R_7 and C_3 are pre-low pass filter, R_8 and C_4 are post-low pass filter. The low-frequency signal is obtained through the pre-low pass filter circuit, which is consistent with the Q_5 frequency. The average value of the low-frequency signal is obtained through the post-low pass filter. The cut-off frequencies of two filter circuits are different because their functions are different. The cut-off frequency of the pre-filter circuit is close to the Q_5 frequency, while the cut-off frequency of the post-filter circuit is far less than that of the pre-filter circuit. The rectangular wave is obtained by comparing the low-frequency signal with the average value.

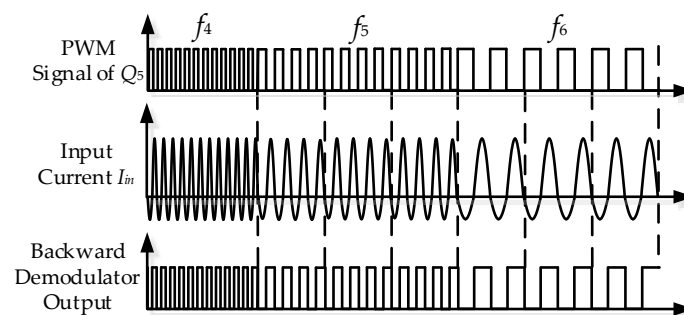


Figure 7. Voltage waveforms of different Q_5 frequencies.

Considering the demodulation frequency range of the primary side, the rectangular wave with stable frequency could be demodulated at the primary side if the Q_5 frequency is set appropriately. Therefore, the Q_5 frequency needs careful consideration.

4. Method of Information Transmission

Based on the above information transmission principles, two modes called predefined mode and continuous data mode are proposed for different application scenarios. Predefined mode is achieved by transmitting specific frequencies so that a series of the predefined action is realized at the opposite side. Continuous data mode is achieved by transmitting modulated signals so that the complex, large information transmission is received.

4.1. Mode A: Predefined Instruction Transmission

For the simple applications, the forward or backward information transmission could be used as a trigger that executes a series of predefined instructions. Based on the above information transmission principle, for example, if the secondary side attempts to ask for the primary side to execute a series of instructions, then the secondary sends a signal to the primary side by changing the switching frequency of Q_5 . The rectangular wave with the same frequency of Q_5 is obtained by the backward demodulator. The DSP controller of primary side recognizes the rectangular wave as a trigger signal and executes the

predefined instructions. When transmitting different predefined instructions, the switching frequency of Q_5 is changed to a specific frequency. The primary side receives the trigger signal and executes the corresponding instructions.

Similarly, when the primary side asks for the secondary side to perform a certain instruction, it transmits signal to the secondary side by changing the working frequency of the converter. Taking backward information transmission as an example, the modulation waveform of Mode A is shown in Figure 8.

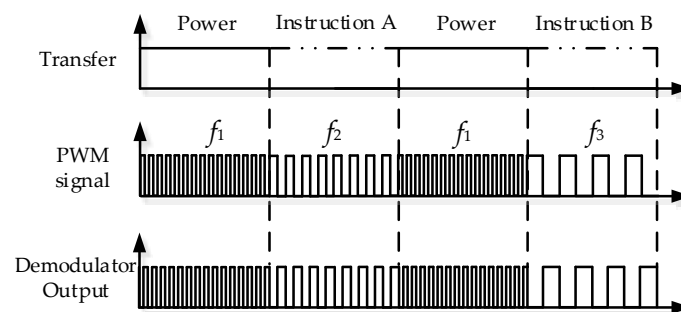


Figure 8. Modulation waveform of predefined instruction backward transmission.

4.2. Mode B: Continuous Data Transmission

For applications where bulk information needs to be transmitted in real time, continuous transmission mode should be used. For the information forward transmission of Mode B, if the working frequency of the converter deviates too much from the resonant frequency, the system generates too much reactive power, which seriously affects the system transmission efficiency. Considering the high efficiency of transmission, the modulation frequency of the forward information transmission should be close to the resonant frequency. For the information backward transmission of Mode B, the demodulation frequency is constrained by the hardware parameters, because the DSP is not able to distinguish if the demodulation frequency deviates too little from the resonant frequency. So, the bandwidth of Mode B is limited.

According to the analysis above, the data information could be transferred by the binary signals. Taking data backward transmission as an example, the modulation waveforms are shown in Figure 9. The switching frequency of Q_5 is set to two different frequencies that represent 1 or 0 signal. The input current frequency of the primary DC voltage source changes as the same frequency as Q_5 . The rectangular wave signals with two different frequencies are demodulated at the primary, and the 1 or 0 signals are identified by the DSP controller of the primary side.

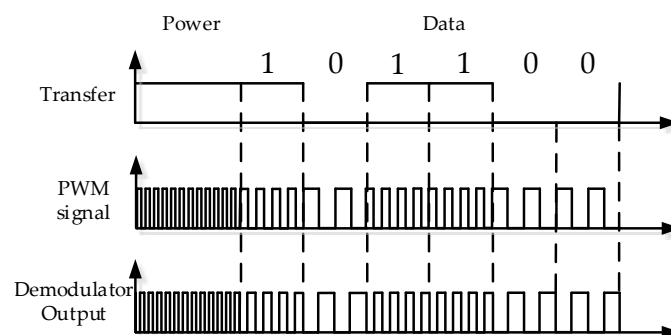


Figure 9. Modulation waveform of data backward transmission.

4.3. Simultaneous Power and Information Transfer Control Algorithm

When the proposed SWIPT system is operating, the converter is controlled to keep the load voltage stable as the information is transferring. The control algorithm of the proposed SWIPT system

is shown in Figure 10. In power transmission, the load voltage is sampled and compared with the reference value of output voltage. The voltage angle of the Q_5 is adjusted in real time to stabilize the output voltage. When transmitting information, the frequency of the control signal is adjusted according to the transmitted signal, the switching frequency of the converter is adjusted during information forward transmission. The switching frequency of Q_5 is adjusted during information backward transmission. After the information transmission is completed, the system frequency is returned to the original frequency.

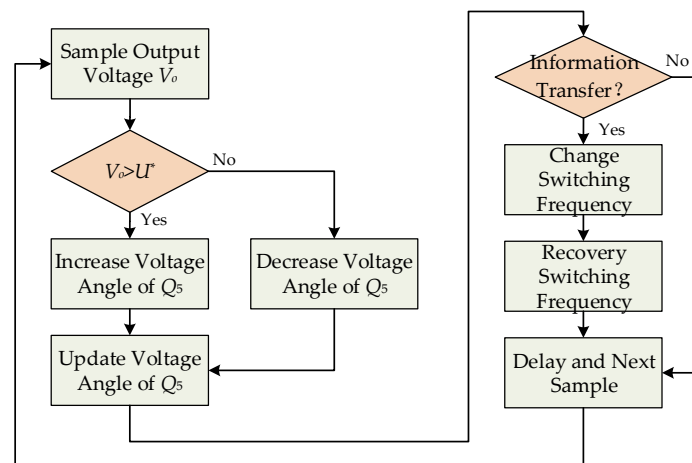


Figure 10. Flow chart of control algorithm.

5. Verifications

In this section, the experiments are carried out to transfer power and information at different frequencies, and the information is transferred at different rates. The resonance frequency of the system is 85 kHz, while 83 kHz is close to the resonant frequency and the system generates very little reactive power. So, 85 kHz and 83 kHz are set as power frequencies and modulation signal frequencies for information forward transmission. As the backward demodulator of experimental platform is able to demodulate the frequency from 4 kHz to 12 kHz, hence 5 kHz and 10 kHz Q_5 frequencies are set as modulation signal frequencies for information backward transmission.

A simulation model is set up in MATLAB/Simulink and an experimental prototype is built. The simulation and experimental results of mode A and mode B with constant load voltage validate the feasibility and effectiveness of the proposed WPT topology and information bidirectional transmission method.

The experimental platform is shown in Figure 11. The DC voltage source is SW-6000W-300V, the controller is TMS320F28335 DSP, the MOSFET is C2M0080120D, the power diode is C4D20120D, and the waveform is acquired using the oscilloscope Tektronix TPS2024B. The system parameters are shown in Table 1.

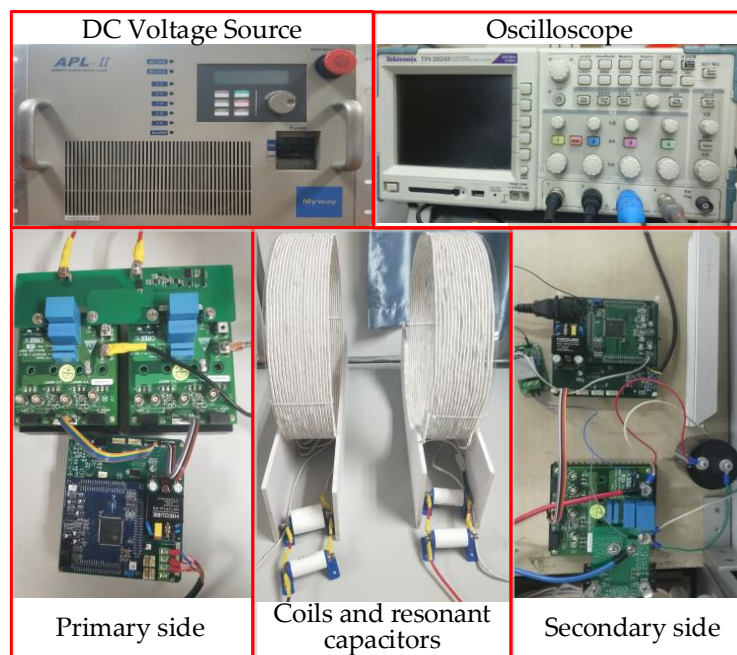


Figure 11. Prototype of proposed SWIPT system.

Table 1. System Parameters.

Parameters	Values
Coil inductance L_1, L_2	175 μH , 219 μH
Capacitance C_1, C_2	20 nF, 16 nF
Resistance R_1, R_2	0.33 Ω , 0.47 Ω
Power frequency f	85 kHz
Input voltage V_{in}	50 V
Mutual inductance M	32 μH
Load resistance R_L	50 Ω
Load voltage V_o	50 V

5.1. Results and Analysis of Information Forward Transmission

The normal power frequency of the system is set to the resonant frequency 85 kHz, as shown in Figure 12. If the power is transferred at a non-resonant frequency, such as 83 kHz, then the system operates at Mode A, i.e., the predefined instruction transmission mode, as shown in Figure 13. For the Mode B, data transmission is carried out by modulating the binary signal, as shown in Figure 14.

The simulation and experimental waveforms of power transmission at 85 kHz are shown in Figure 12. The simulation and experimental waveforms are the voltage of C_s , output of forward demodulator and load voltage in turn. The power frequency is set to 85 kHz, and the voltage frequency of C_s is also 85 kHz. The rectangular wave signal whose frequency is consistent with the power frequency is obtained by forward demodulator. At this time, the load voltage is maintained at 50 V due to the feedback control of secondary side.

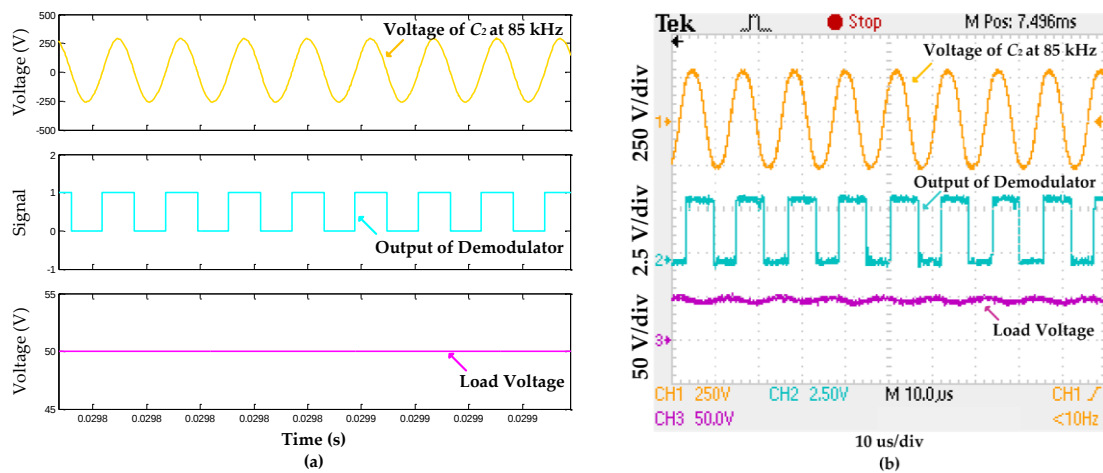


Figure 12. The transmission waveform of power transmission at 85 kHz (a) simulation result (b) experimental result.

When the power frequency deviates from the resonant frequency, it can be used as the transmission instruction for predefined mode. For example, the power transmission frequency is changed to 83 kHz, then the voltage frequency of the C_s is also changed. The rectangular wave of 83 kHz frequency is obtained by forward demodulator, and the predefined instruction transmission from the primary side to the secondary side is completed. When the power frequency deviates from the resonant frequency, the feedback control of secondary side can keep the load voltage constant at 50 V. The simulation and experimental waveforms of power transmission at 83 kHz are shown in Figure 13. The simulation and experimental waveforms are the voltage of C_s , output of forward demodulator and load voltage in turn.

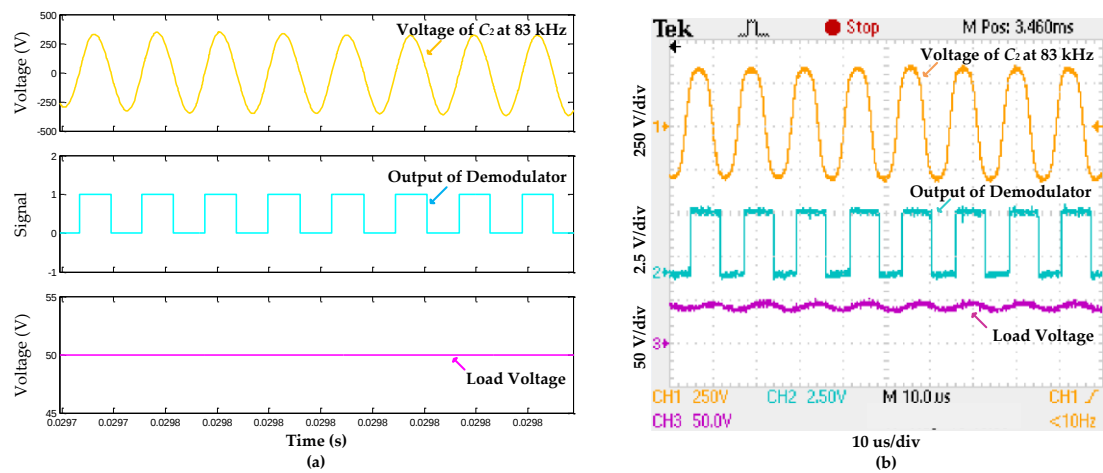


Figure 13. The transmission waveform of power transmission at 83 kHz (a) simulation result (b) experimental results.

The simulation and experimental waveforms of information forward transmission waveforms at 1 kbit/s rate are shown in Figure 14. The simulation and experimental waveforms are transmission signals, the voltage of C_s and load voltage in turn. The modulation signal "1" corresponds to 83 kHz and modulation signal "0" corresponds to 85 kHz. According to Figure 14, the load voltage keeps a constant of 50 V during data forward transmission.

5.2. Results and Analysis of Information Backward Transmission

Figures 15 and 16 display the transmission waveforms as the frequency of Q_5 is 5 kHz and 10 kHz, respectively. When the predefined instructions can not meet the system requirements, data transmission is carried out by modulating the 1, 0 signal, as shown in Figure 17.

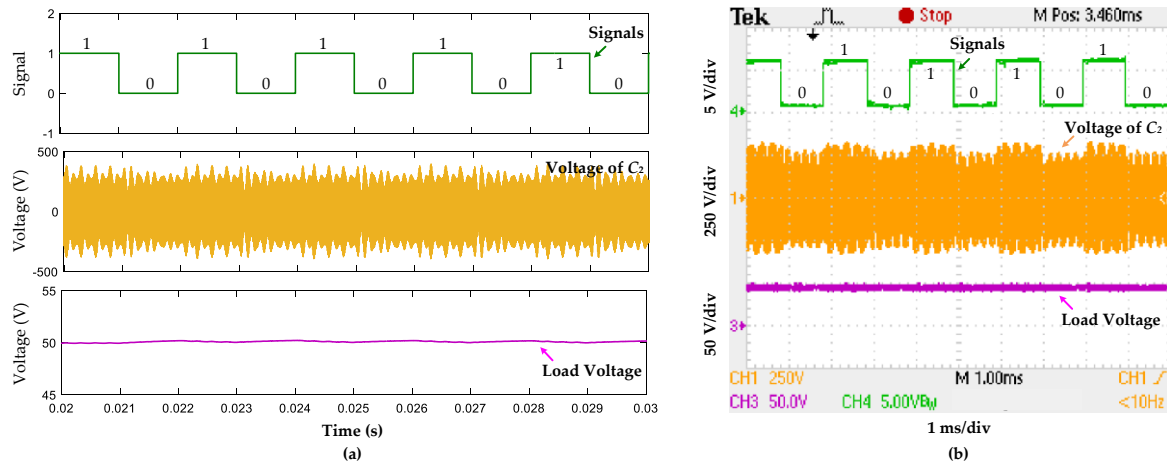


Figure 14. Data forward transmission waveforms at 1 kbit/s rate (a) simulation result (b) experimental results.

The Q_5 frequency is set to 5 kHz, the frequency of input current I_{in} changes as the same frequency as Q_5 . The rectangular wave of 5 kHz frequency is obtained by backward demodulator, and the predefined instruction transmission from the secondary side to primary side is completed. When the Q_5 frequency changes, the feedback control of secondary side keeps the load voltage constant at 50 V. The simulation and experimental waveforms of Q_5 frequency at 5 kHz are shown in Figure 15. The waveforms are the control signal of Q_5 , output of pre-low pass filter and post-low pass filter, output of backward demodulator, respectively.

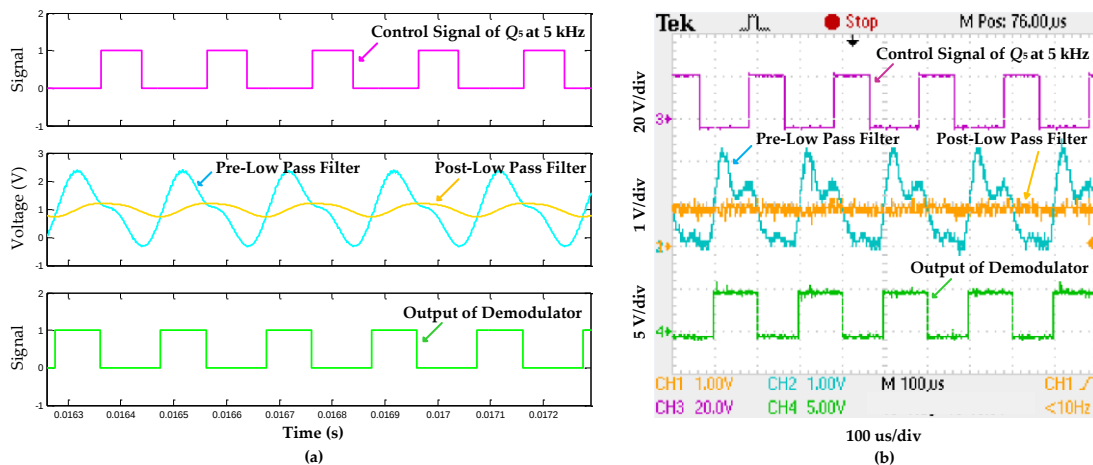


Figure 15. The backward transmission waveform of Q_5 frequency at 5 kHz (a) simulation result (b) experimental result.

The simulation and experimental waveforms of Q_5 frequency at 10 kHz are shown in Figure 16. The waveforms include the control signal of Q_5 , output of pre-low pass filter and post-low pass filter, output of backward demodulator, respectively. The Q_5 frequency is set to 10kHz, the input current I_{in} changes at the same frequency. By comparing the output of the pre-low pass filter and the post-low pass filter, the rectangular wave with the 10 kHz frequency is obtained.

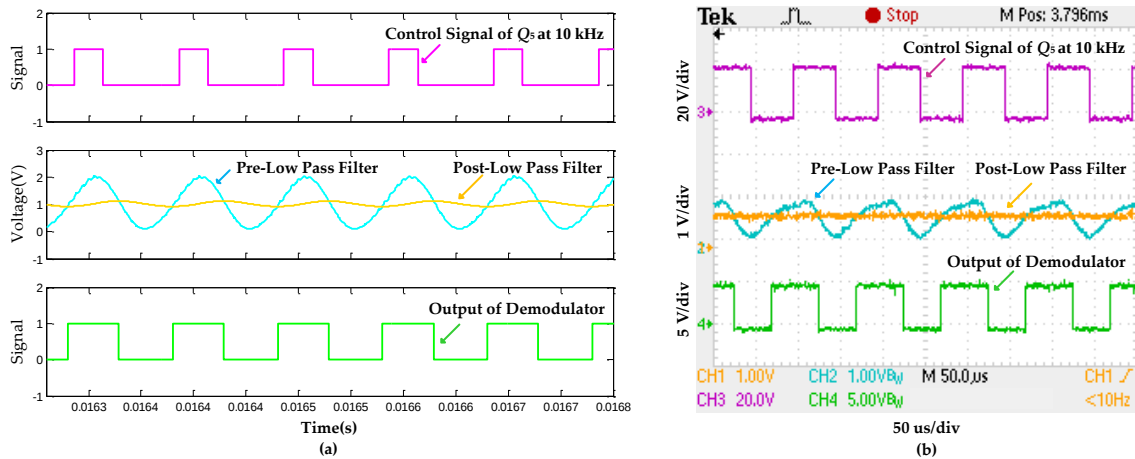


Figure 16. The backward transmission waveform of Q_5 frequency at 10 kHz (a) simulation result (b) experimental result.

Figure 17 shows the simulation and experimental waveforms of information backward transmission waveforms at 1 kbit/s rate. The waveforms include the transmission signals, the control signal of Q_5 , output of backward demodulator and load voltage, respectively. The modulation signal "1" corresponds to Q_5 frequency of 10 kHz and modulation signal "0" corresponds to 5 kHz. The modulation rate of the transmission signal is 1 kbit/s and the Q_5 frequency varies with the same frequency. According to Figure 17, the load voltage keeps constant of 50 V during data backward transmission.

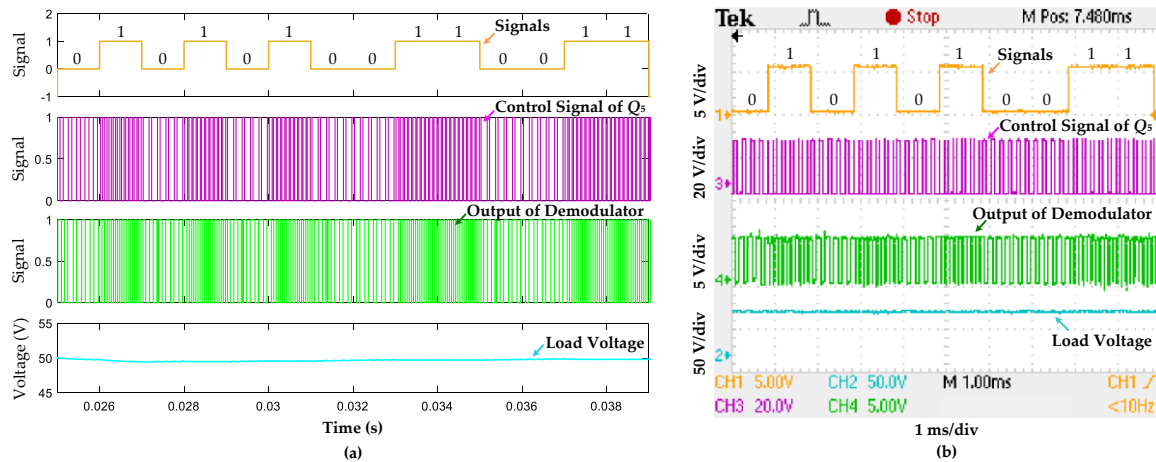


Figure 17. Data backward transmission waveforms at 1 kbit/s rate (a) simulation result (b) experimental result.

6. Conclusions

In this paper, a new SWIPT topology is proposed, together with the information bidirectional transmission method. The working principle of the system is analyzed and the relationship between variables is deduced. The constant voltage output feedback control strategy is designed to achieve constant load voltage. The information forward transmission method based on FSK and the information backward transmission method based on chopper control are proposed. Two modes of information transmission are proposed for different working conditions. An experimental platform is built to verify the proposed topology and information bidirectional transmission method. The simulation and experiment verify that the information is able to be transferred in both directions, and the load voltage keeps stable during information transmission.

By the proposed topology, the secondary requires only one extra switch so that the system is equipped with the capability of bidirectional information transmission. This provides a low-cost solution for upgrading a traditional WPT system to a SWIPT system.

Author Contributions: Conceptualization, J.W. and N.J.; Methodology, J.W. and C.Z.; Software, N.J. and S.H.; Validation, C.Z., S.H. and D.M.; Writing—original draft preparation, J.W., C.Z. and D.M.; Writing—review and editing, J.W. and N.J.

Funding: This research was funded by NSFC (grant number U1604136) and by ZZULI Graduates Project (grant number 2018034).

Conflicts of Interest: The authors declare no conflict of interest.

References

- Garcia, D.T.; Vazquez, J.; Roncero, S.P. Design, implementation issues and performance of an inductive power transfer system for electric vehicle chargers with series-series compensation. *IET Power Electron.* **2015**, *8*, 1920–1932. [\[CrossRef\]](#)
- Hui, S.Y.R.; Ho, W.C. A new generation of universal contactless battery charging platform for portable consumer electronic equipment. *IEEE Trans. Power Electron.* **2005**, *20*, 620–627. [\[CrossRef\]](#)
- Sallan, J.; Villa, J.L.; Llombart, A. Optimal design of ICPT systems applied to electric vehicle battery charge. *IEEE Trans. Ind. Electron.* **2009**, *56*, 2140–2149. [\[CrossRef\]](#)
- Wang, T.; Liu, X.; Jin, N.; Tang, H. Wireless Power Transfer for Battery Powering System. *Electronics* **2018**, *7*, 178. [\[CrossRef\]](#)
- Abou Houran, M.; Yang, X.; Chen, W. Magnetically Coupled Resonance WPT: Review of Compensation Topologies, Resonator Structures with Misalignment, and EMI Diagnostics. *Electronics* **2018**, *7*, 296. [\[CrossRef\]](#)
- Han, L.; Li, L.M. Integrated Wireless Communications and Wireless Power Transfer: An Overview. *Phys. Commun.* **2017**, *25*, 555–563. [\[CrossRef\]](#)
- Thrimawithana, D.J.; Madawala, U.K.; Neath, M. A Synchronization Technique for Bidirectional IPT Systems. *IEEE Trans. Ind. Electron.* **2013**, *60*, 301–309. [\[CrossRef\]](#)
- Liu, X.; Jin, N.; Yang, X.; Wang, T. A Novel Synchronization Technique for Wireless Power Transfer Systems. *Electronics* **2018**, *7*, 319. [\[CrossRef\]](#)
- Wang, Z.; Li, Y.; Sun, Y. Load detection model of voltage-fed inductive power transfer system. *IEEE Trans. Power Electron.* **2013**, *28*, 5233–5243. [\[CrossRef\]](#)
- Johari, R.; Krogmeier, J.V.; Love, D.J. Analysis and practical considerations in implementing multiple transmitters for wireless power transfer via coupled magnetic resonance. *IEEE Trans. Ind. Electron.* **2014**, *61*, 1774–1783. [\[CrossRef\]](#)
- Ju, X.; Dong, L.; Huang, X. Switching technique for inductive power transfer at high-Q regimes. *IEEE Trans. Ind. Electron.* **2015**, *62*, 2164–2173. [\[CrossRef\]](#)
- Li, M.; Liu, D.; Gong, C.; Qiao, W. A 3-coil simultaneous power and uplink data transmission inductive link for battery-less implantable devices. In Proceedings of the 2017 IEEE International Symposium on Circuits and Systems, Baltimore, MD, USA, 28–31 May 2017; pp. 1–4.
- Peng, K.; Tang, X.; Mai, S.P.; Wang, Z.H. A Simultaneous Power and Downlink Data Transfer System with Pulse Phase Modulation. *IEEE Trans. Circuits Syst.-II: Express Briefs* **2019**, *66*, 808–812. [\[CrossRef\]](#)
- Wu, J.; Zhao, C.; Lin, Z. Wireless Power and Data Transfer via a Common Inductive Link Using Frequency Division Multiplexing. *IEEE Trans. Ind. Electron.* **2015**, *62*, 7810–7820. [\[CrossRef\]](#)
- Lee, H.; Lee, K.J.; Kim, H. Wireless information and power exchange for energy-constrained device-to-device communications. *IEEE Internet Things J.* **2018**, *5*, 3175–3185. [\[CrossRef\]](#)
- Brusamarello, V.J.; Blauth, Y.B.; De-Azambuja, R. Power transfer with an inductive link and wireless tuning. *IEEE Trans. Instrum. Meas.* **2013**, *62*, 924–931. [\[CrossRef\]](#)
- Sun, Y.; Yan, P.X.; Wang, Z.H. The parallel transmission of power and data with the shared channel for an inductive power transfer system. *IEEE Trans. Power Electron.* **2016**, *31*, 5495–5502. [\[CrossRef\]](#)
- Yu, C.; Lu, R.; Su, C. Study on wireless energy and data transmission for long-range projectile. *IEEE Trans. Plasma Sci.* **2013**, *41*, 1370–1375.

19. Wang, G.; Wang, P.; Tang, Y. Analysis of dual band power and data telemetry for biomedical implants. *IEEE Trans. Biomed. Circuits Syst.* **2012**, *6*, 208–215. [[CrossRef](#)]
20. Yilmaz, G.; Atasoy, O.; Dehollain, C. Wireless energy and data transfer for in-vivo epileptic focus localization. *IEEE Sens. J.* **2013**, *13*, 4172–4179. [[CrossRef](#)]
21. Al-Kalbani, A.I.; Yuce, M.R.; Redoute, J.M. Design methodology for maximum power transmission, optimal ber-snr and data rate in biomedical implants. *IEEE Commun. Lett.* **2013**, *17*, 1897–1900. [[CrossRef](#)]
22. Yao, C.; and Zhang, G. Design and realization of the collective meter-reading system with power lines carrier. *Power System Protection and Control.* **2008**, *36*, 77–79.
23. Diaz Lantada, A.; González, B.; Carlos; Lafont, M.P. Novel system for bite-force sensing and monitoring based on magnetic near field communication. *Sensors* **2012**, *12*, 11544–11558. [[CrossRef](#)] [[PubMed](#)]
24. Huang, Y.G.; Fang, C.; Li, X.F. Contactless power and data transmission for underwater sensor nodes. *Eurasip J. Wirel. Commun. Netw.* **2013**, *2013*, 81. [[CrossRef](#)]
25. Besnoff, J.; Abbasi, M.; Ricketts, D.S. High data-rate communication in near-field rfid and wireless power using higher order modulation. *IEEE Trans. Microw. Theory Tech.* **2016**, *64*, 401–413. [[CrossRef](#)]
26. Sonkusale, S.R.; Luo, Z. A Wireless Data and Power Telemetry System Using Novel BPSK Demodulator for Non-Destructive Evaluation of Structures. In Proceedings of the IEEE SENSORS, Atlanta, GA, USA, 28–31 October 2007; pp. 300–303.
27. Jiang, D.; Cirmirakis, D.; Schormans, M.; Perkins, T.A.; Donaldson, N.; and Demosthenous, A. An Integrated Passive Phase-Shift Keying Modulator for Biomedical Implants with Power Telemetry over a Single Inductive Link. *IEEE Trans. Biomed. Circuits Syst.* **2017**, *11*, 64–77. [[CrossRef](#)] [[PubMed](#)]
28. Mandal, S.; Sarpeshkar, R. Power-efficient impedance-modulation wireless data links for biomedical implants. *IEEE Trans. Biomed. Circuits Syst.* **2008**, *2*, 301–315. [[CrossRef](#)] [[PubMed](#)]
29. Tang, Z.; Smith, B.; Schild, J.H. Data transmission from an implantable biotelemetry by load-shift keying using circuit configuration modulator. *IEEE Trans. Biomed. Eng.* **1995**, *42*, 524–528. [[CrossRef](#)]
30. Xu, W.R.; Luo, Z.Y.; Sonkusale, S. Fully Digital BPSK Demodulator and Multilevel LSK Back Telemetry for Biomedical Implant Transceivers. *IEEE Trans. on Circuits and Systems II: Express Briefs.* **2009**, *56*, 714–718.
31. Zhao, J.; Yao, L.; Xue, R.F.; Li, P.; Je, M.Y. An Integrated Wireless Power Management and Data Telemetry IC for High-Compliance-Voltage Electrical Stimulation Applications. *IEEE Trans. Biomed. Circuits Syst.* **2016**, *10*, 113–124. [[CrossRef](#)]
32. Ha, S.; Kim, C.; Park, J.; Joshi, S.; Cauwenberghs, G. Energy Recycling Telemetry IC with Simultaneous 11.5 mW Power and 6.78 Mb/s Backward Data Delivery over a Single 13.56 MHz Inductive Link. *IEEE J. Solid-State Circuits.* **2016**, *51*, 2664–2678. [[CrossRef](#)]
33. Ha, S.; Kim, C.; Park, J.; Joshi, S.; Cauwenberghs, G. Energy-Recycling Integrated 6.78-Mbps Data 6.3-mW Power Telemetry over a Single 13.56-MHz Inductive Link. In Proceedings of the 2014 Symposium on VLSI Circuits Digest of Technical Papers, Honolulu, HI, USA, 10–13 June 2014; pp. 1–2.

