IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received October 7, 2019, accepted October 24, 2019, date of publication October 29, 2019, date of current version November 15, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2950084

A Novel Method of Wireless Power Transfer Identification and Resonance Decoupling Based on Frequency Hopping Communication

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This work was supported in part by the National Key Research and Development Program of China under Grant 2017YFB1201003-022, in part by the National Natural Science Foundation of China under Grant 51577133, Grant 51607121, and Grant 51877151, and in part by the Program for Innovative Research Team in University of Tianjin under Grant TD13-5040.

ABSTRACT Aiming at the risk of electricity theft of wireless power transfer (WPT) technology due to its untargeted and non-directional characteristics, a novel method of identification and resonance decoupling based on frequency hopping communication is proposed. The basic principle of the identification method is to make the resonant frequency of transmitter coil and receiver coil jump synchronously and randomly according to the pseudo-random code sequence, which can identify the load in single-source single-user mode and single-source multi-user mode respectively by calculating energy consumption ratio. And if user is illegal, then the resonant frequency of system jumps randomly to cut off the power, which is named resonance decoupling. The experimental circuit is designed on the basis of theoretical analysis and the method is verified. The test results are consistent with theoretical analysis, which has proved the validity of the method. This paper not only provides a solution to the power management of WPT system, but also is a support for the measurement of electricity, moreover, it is conducive to the further application and promotion of WPT technology.

INDEX TERMS Frequency hopping communication, identification and resonance decoupling, pseudo-random code, wireless power transfer.

I. INTRODUCTION

Wireless Power Transfer (WPT) is a new technology which can bring innovatory progress in power transmission field. The common ways to realize WPT technology are coupled magnetic resonance (CMR), inductive power transfer (IPT) and capacitive power transfer (CPT), in addition to laser and ultrasonic modes [1]–[6]. Among them, CMR is one of the strongest candidates because of its relatively larger transfer distance, high efficiency and non-radioactive feature. Much of the literature on CMR takes as its focus several issues, such as characteristics of power transfer efficiency (PTE, the ratio of the power received by the load to the power emitted by the transmitter coil) [7]–[9], characteristics of transmission [10]–[12] and modelling of CMR system [13], [14], which had achieved excellent research results.

The principle of the CMR shows that coils with the same resonant frequency can realize efficient power transfer at a medium distance [15]–[17]. However, its untargeted feature increases the risk of electricity theft. To prevent the risk, much previous research have focused on the method of identification and resonance decoupling. Identification is used to determine whether the user is legal, and the method of cutting off the power with illegal users is referred to as resonance decoupling.

Currently there are several identification methods. Bar code recognition and optical recognition depend on the surface characteristics of the object being identified [18], [19]. Due to the bar code or appearance of the recognized WPT is easy to be copied, it is not suitable in WPT. Biometric recognition requires physical contact between recognition device, which has no application value in WPT [20], [21]. For magnetic recognition, the data of objects may be damaged in WPT, which affects the accuracy [22]. IC cards require

The associate editor coordinating the review of this manuscript and approving it for publication was Fei Lu.

contact to read and write data, only can be applied in situations with a certain transfer distance [23]. For identification of WPT in electric vehicle, radio frequency identification (RFID) is widely used [24], [25]. Although the method is easy to implement, it fails to achieve resonant decoupling due to its poor confidentiality, especially when charging multi users at the same time [26].

This paper proposed a novel method of identification and resonance decoupling based on frequency hopping (FH) communication. And the innovation of this method is as follows: a) The method can cut off the power of illegal users with rarely influence the legal users, which is the traditional solutions cannot. b) For the proposed identification and resonance decoupling method, the identification part and the resonance decoupling part are united as one, which are separated for traditional ways. Therefore, the traditional method is more complex and less reliable, especially for multi-user charging. The method proposed in this paper can avoid the disadvantages of the traditional one, which can improve efficiency and reliability.

The principle of identification based on FH is that the resonant frequency of the transmitter (Tx) coil and receiver (Rx) coil can be changed randomly according to pseudo-random (PR) code. In such system, the necessary condition for normal work is that the three key elements (Hopping clock, Hopping frequency and Hopping sequence) of receivers are exactly the same as those on the transmitter. And the user who can receive power every hop is legal. As for illegal users, the power transmission channel can be cut off by changing the resonant frequency of the transmitter, which is named resonance decoupling. The identification and resonance decoupling method has strong anti-tracking and anti-interference ability due to its randomness, and the rule of FH cannot be obtained except the users authorized.

The rest of the paper is organized as follows. Section II describes the principle of identification and resonance decoupling based on FH communication. The more detailed method for WPT and its implementation are showed in Sections III. Section VI discusses the experimental results, followed by the conclusion in Section V.

II. PRINCIPLES OF IDENTIFICATION AND RESONANCE DECOUPLING BASED ON FH COMMUNICATION

A. THE PRINCIPLE OF FH COMMUNICATION

FH communication is one of the ways of spread spectrum communication, and its working principle is that the carrier frequency of the transmitted and received signals discretely hopped according to PR code [27], [28]. Because of its anti-tracking and anti-interference ability, FH method is widely used in the field of wireless communication. The schematic of FH communication as shown in Fig. 1.

The work flow of FH communication system is: firstly, the spread-spectrum code generator of the transmitter outputs a FH instruction, which controls the frequency of signal $a(t)$ of the frequency synthesizer changes randomly after being decoded, then the antenna sends the transmission signal $s(t)$ after mixed with data signal $d(t)$ by a multiplier. In receiving system, the synchronization technology and the same FH instruction as that of transmitter need to be used to control the frequency synthesizer of the receiver to output the signal $b(t)$, which changes as same as $a(t)$. Then, the output signal $v(t)$ can be obtained after filtering, mixing and demodulating, and finally the original data signal can be obtained. FH communication can not only ensure the integrity of the signal, but also its encryption.

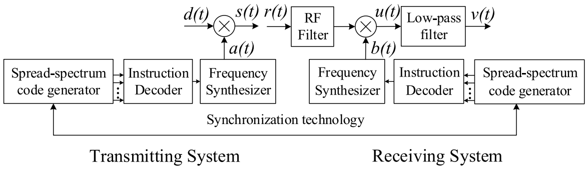


FIGURE 1. Schematic of FH communication.

PR code is also called as pseudo-noise sequence, refers to the sequence that has random characteristics and can be repeatedly generated. Due to its randomness, near-white noise, certainty and repeatability, PR code has been widely used in information security, wireless communication and cryptography. This paper combines PR code with WPT to propose an identification method with high reliability. The resonant frequencies of the Tx coil and Rx coil are randomly changed according to binary m-sequence, which can be generated by the feedback shift register and copied. To realize the resonant frequency of transmitter and receiver hop synchronously, the synchronization technology is used. And the purpose of identification has been realized preliminarily.

B. THE PRINCIPLE OF IDENTIFICATION

The criterion for identification is to determine whether the three key elements (Hopping clock, Hopping frequency and Hopping sequence) of transmitter and those of receiver are exactly the same. If the resonant frequency of Tx coil and Rx coil maintain a synchronous transition, then the effective power transmission can be achieved; otherwise, the power transmission will be cut off.

In WPT system, resonant coils have multiple natural resonant frequencies. FH can be achieved through this feature, i.e. passive FH. So we adjust the resonant frequency by changing the combination of tuning capacitors of coils [29], [30]. By controlling the relay groups of tuning capacitors can make number of the resonant frequencies range from dozens to hundreds, which can improve the effectiveness of the identification.

In this case, the synchronous state of Tx coil between Rx coil can be determined by detecting whether the PTE fluctuates. If the receiver can be authenticated by the identification system of transmitter, then the receiver can always receive power even if the resonant frequency hops randomly. Otherwise, if the user is illegal, the change of resonant frequency on each side cannot be synchronized, and the load will rarely

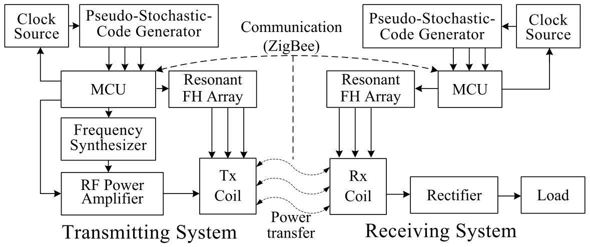


FIGURE 2. Schematic diagram of FH identification system based on FH communication.

receive power or receiver lower power, so as to achieve the purpose of identification. During the identification process, the power transmission is uninterrupted, which can guarantee the legal users power supply and cut off the coupling of the illegal users among the single-multi mode, which is especially important in the CMR-WPT of medium-distance.

FH should be irregular to ensure effective identification; however, it is difficult to be applied in practice if it is completely random. Therefore, PR code is used to control the hopping frequency. Pseudo-random is a kind of "fake" random state. In the FH identification system of the paper, the transmitter and the legal receiver have the same predetermined transition rules of FH.

The method of identification is to convert the PR code into a FH instruction to control the frequency of the output signal of the frequency synthesizer so as to change the frequency of the power source and coils. In order to achieve high PTE, the resonant frequency is fixed in conventional CMR system. However, although the identification method proposed requires that the resonant frequency hopping randomly, identification can still be achieved without affecting PTE according to experimental results.

In order to ensure that the resonant frequency of the receiver and the transmitter are the same, the frequency synthesizer of user need to be controlled by the same FH instruction as that of the transmitter to output the FH signal synchronously. The FH instruction is generated by the PR code generator as well. Fig. 2 shows a schematic diagram of FH identification system based on FH communication.

The process of identification is: the transmitter and the receiver interact with each other via wireless communication after starting the system. Then the FH instruction generated by transmitter PR code generator to control the frequency of the signal so that the frequency of power source and the resonant frequency of Tx coil jump randomly. At the same time, the same FH instruction generated by the receiver PR code generator to change the resonant frequency of Rx coil synchronously. The FH sequence depends on the decoded PR code.

As mentioned above, the necessary condition of working is that only when the three key elements of receiver are exactly the same as those of the transmitter. Actually, the frequency and duration of FH are determined by combining the FH instruction with the time-frequency matrix. To further explain this prerequisite, a schematic diagram is drawn as shown in Fig. 3. As shown in Fig. 3(a) and (b), the state of both sides is out of synchronization due to the different starting time or sequence of FH. Only when the three elements are all the same, state changes synchronously as shown in (c). And illegal users cannot harvest power because the three key elements cannot be met at the same time.

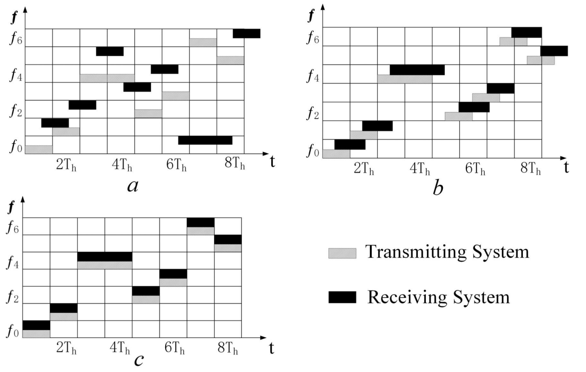


FIGURE 3. Schematic diagram of identification conditions. (a) Only frequency of FH is the same. (b) Frequency of FH & FH sequence are the same. (c) Frequency of FH, FH sequence & Hopping clock are the same.

C. THE PRINCIPLE OF RESONANCE DECOUPLING

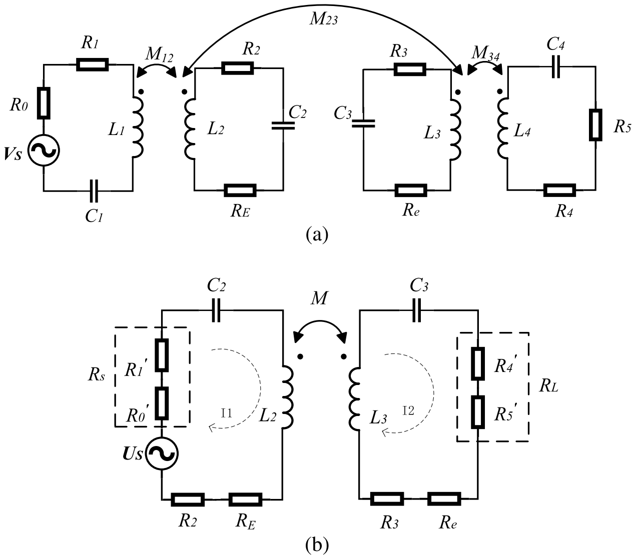
In WPT system, although illegal users are identified, if the power channel of illegal users is not cut off in time, the energy security and stability of the system will be destroyed. To prevent the risk, resonance decoupling is necessary. By changing the operating frequency according to pre-determined FH instruction, the Rxs of the illegal user can be detuned and the power can be cut off as well.

Resonance decoupling can be achieved by changing the coil parameters, such as: coil structure, copper area of coil, number of turns, tuning capacitors, etc. Among them, only changing the tuning capacitor can accurately control resonant frequency to change.

As mentioned above, the power of illegal users can be cut off by the proposed method even there are more than one receiver, which is the traditional solutions cannot.

D. THE PRINCIPLE OF WPT

The circuit topology of the system is shown in Fig. 4(a). V_S is the excitation power supply, R_0 is the internal resistance, R_5 is the load resistance. R_1, R_2, R_3 and R_4 are the resistances of excitation coil, Tx coil, Rx coil and load coil respectively. R_E, R_e are the equivalent AC loss resistance of Tx coil and Rx coil. C_1, C_2, C_3 and C_4 are capacitors of exciting coil, Tx coil, Rx coil and load coil respectively. The inductances of L_1, L_2, L_3 and L_4 are respectively excitation coil, Tx coil, Rx coil and load coil. Simplified circuit analysis, according to the principle of equivalence, the circuit of excitation coil is equivalent to the Tx coil, which is equivalent to adding an inductive electromotive force with impedance in the Tx coil; the load coil is equivalent to adding a reflection impedance to



(a)

(b)

FIGURE 4. (a) Equivalent circuit for WPT with four-coil structure; (b) Simplified equivalent circuit for WPT.

the Rx coil, and its equivalent circuit is shown in the Fig. 4(b). U_S, R'_0, R'_1 are equivalent parameters of excitation coils V_S, R_0 and R_1, R'_4, R'_5 are equivalent parameters of load coils R_4 and R_5, and M is mutual inductance M_{23} between Tx coil and Rx coil. In the simplified circuit, R_S, R_L can be the equivalent internal resistance and load respectively.

When the system is in resonance, the impedance of each coil will be pure resistance, thus the PTE can be expressed in (1), as shown at the bottom of this page.

In the transmission process, the resonant frequency is changed by the switching capacitances of Tx coil and Rx coil. The Tx coil and Rx coil can maintain time resonance. So only angular frequency is a variable in (1) and (2). In order to analyze the power and efficiency characteristics of the system, other variables are fixed. The parameters are as follows: $R_S = R_L = 50\ \Omega$, $R_2 = R_3 = 0.5\ \Omega$, $L_1 = L_2 = 20\ \mu$H. In addition, through the analysis of the finite element simulation model, the equivalent resistance value of the AC loss of the circuit model is obtained by $R_E = R_e = 6\ \Omega$.

As shown in Fig. 5, the simulation and experimental trends are consistent, and the experimental results show that the PTE fluctuation is slightly larger. From the simulation and experimental results, the PTE is basically unchanged during the FH process.

III. METHOD OF IDENTIFICATION AND RESONANCE DECOUPLING FOR WPT

According to the principle of WPT [31]–[33], the wireless power transfer with identification and resonance decoupling is shown in Fig. 6(a). The model mainly consists of the following parts [34]: Class E power amplifier (PA), automatic impedance matching device (AIM device), source coil (S), Tx coil, FH array of Tx coil (A_0), Rx coil, FH array of Rx coil (A_i, $i = 1,2,3 \ldots n$), load coil (L_i, $i = 1, 2, 3 \ldots n$) and loads.The AIM device guarantees the constant power input to the Tx coil. It can also be replaced by fixed-point impedance matching or adjusting the output of the PA according to the

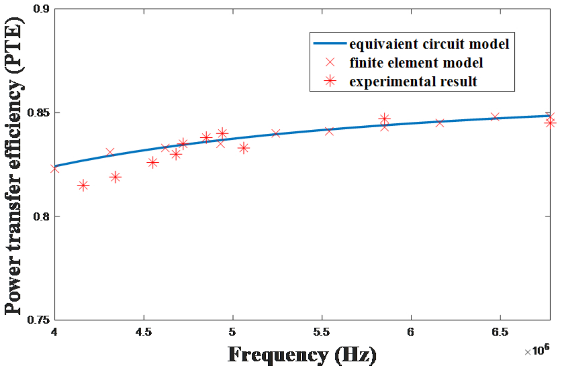
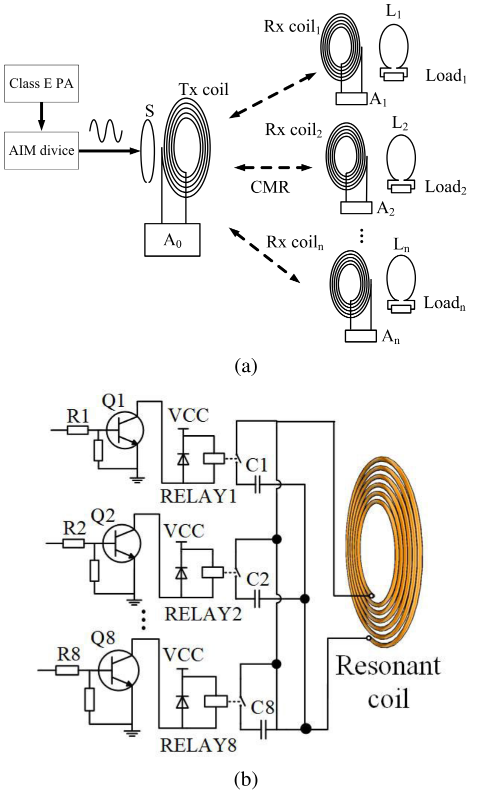


FIGURE 5. PTE changes in FH process in experiments and simulations.



(a)

(b)

FIGURE 6. (a) Wireless power transfer with identification and resonance decoupling; (b) Resonant FH array of coil.

$$\eta = \frac{R_L\,(\omega M)^2}{\left[(R_2+R_E)(R_3+R_e)+(R_2+R_E)R_L+(\omega M)^2\right]\left[(R_3+R_e)+R_L\right]} \tag{1}$$

actual situation. Class E PA (frequency range is 1-30MHz) supply for S coil high-frequency sinusoidal AC voltage, and S coil transmits the power to the Tx coil through magnetic coupling. Then Rxs received power from Tx through CMR. Rxs transmit power to L_i coils through magnetic coupling respectively. Finally, the load obtained power after rectification and conversion. Both the Tx coil and the Rx coil adopt a parallel compensation structure, and the input power of the Tx coil remains constant during the FH process.

The operating frequency is tuned by changing the combination of the parallel capacitors of the coil through A_0 to A_i. The diagram of FH array, which consists of 8 capacitors, shown in Fig. 6(b). RELAYi and Ci ($i = 1, 2, \ldots, 8$) represent the relay control modules and capacitors respectively. After receiving the switching signal, RELAYi switches according to the corresponding instruction to control resonant frequency of the coil.

The system consists of transmitting and receiving system. The data communication is completed by the ad-hoc network made up of ZigBee communication modules. The transmitting system includes the master micro-controller unit (MCU), direct digital synthesizer (DDS), Class E PA, AIM device, ZigBee module, Tx coil and its FH array, etc. DDS generates high-frequency sinusoidal signal, which is amplified by RF amplifier, and then transmitted by Tx coil after automatic impedance matching device. At the same time, the MCU controls FH array of Tx coil according to the PR code to change the operating frequency of the coil. And MCU can control the power amplifier on or off as well.

Receiving system includes MCU, ZigBee module, rectifier circuit, Rx coil and it's FH array, which is the same as that of the transmitter. The interaction between two sides is achieved through ZigBee A and B. After rectification, the power is supplied to the load, and the power is detected by the MCU in real time.

In practice, the number of users generally changes dynamically, when the number of users is more than one, it is more difficult to decouple illegal users without affecting the legal users. Thus, we divide the identification and resonance decoupling method into two modes. One is single-single mode, that is, single receiver harvests power from single transmitter; the other is single transmitter offer power to multiple receivers at the same time (i.e., Single-multi mode). The distance between Tx and Rx is fixed during the identification and resonance decoupling process, to reduce its influence on PTE. The flow chart of the main process as shown in Fig. 7.

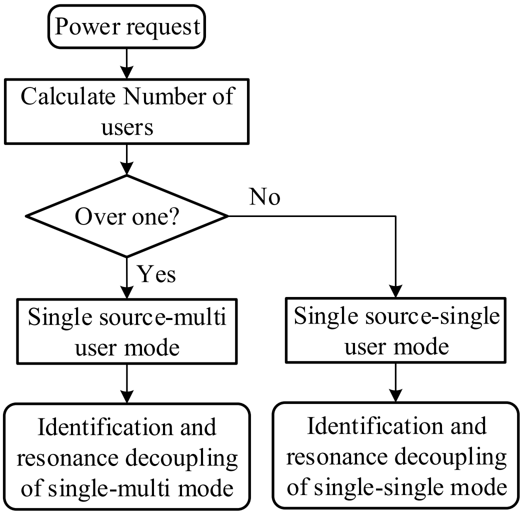


FIGURE 7. The flow chart of main process.

A. THE IDENTIFICATION AND RESONANCE DECOUPLING METHOD OF SINGLE-SINGLE MODE

When the transmitter receives only one power request, the identification and resonance decoupling method of single-single mode is performed. In the mode, the transmitter sends the time synchronization signal (including the starting time of FH and the initial PR code) to the receiver, then start the identification process. Transmitter and receiver switch capacitors synchronously, then measure PTE every time. The test cycle is set to 6 based on premise of FH time, recognition accuracy, hardware cost and software cost. The number times of FH can be changed (higher or lower) if there are other requirements. It is almost impossible for an illegal user to receive energy for six consecutive times, which can ensure the security of the legitimate user power supply. The change of frequency after FH and the influence of coil quality factor on PTE fluctuation are fully considered in the selection of FH each time. Therefore, the judgment of legal or not is based on the fact that whether the PTE fluctuates after switching for 6 times in a row.

After identification, legal users can work properly, and illegal users should be decoupled. The process is as follows: First, the system judge whether the user can receive power at main operating frequency or not, if yes, hop the frequency once and then detects the status. If the power can still be received, continue to hop until the power be cut off. In extreme cases, if the power can still be received by illegal user after frequency hopping for six times in a row, then the MCU will cut off the power and alarm. In addition, if the decoupling time is required or the illegal user always receives a small amount of energy leading to decoupling failure. The resonance decoupling judgment standard (power received) can also be adjusted according to requirements, such as PTE greater than 5% or other values as needed. The flow chart of identification and resonance decoupling method of single-single mode as shown in Fig. 8.

B. THE IDENTIFICATION AND RESONANCE DECOUPLING METHOD OF SINGLE-MULTI MODE

When the transmitter receives multiple (two or more) power requests simultaneously, the identification and resonance decoupling method of single-multi mode is performed. For single-multi mode, it is difficult to decouple one user by means of FH due to the multi-user working at the same frequency. And it is hard to ensure the stable power transmission of legal users during the decoupling as well. Therefore,

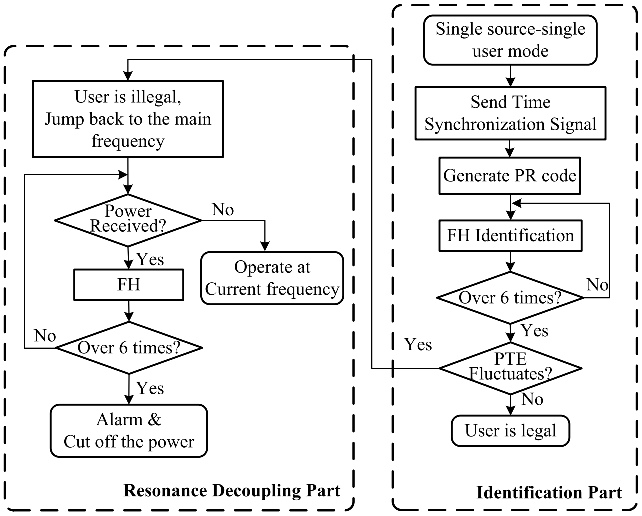


FIGURE 8. **The flow chart of identification and resonance decoupling method of single-single mode.**

the energy consumption ratio (ECR) is adopted to judge the presence of illegal users or not.

In the mode, the transmitter sends the time synchronization signal to the receivers, then start identification process. It is judged whether the system has an illegal user by controlling the DDS amplitude to keep the transmission power constant. When the operating frequency changes, the system make statistics on the power of users. The energy consumption ratio (ECR) is defined as:

$$ECR = \frac{\sum_{i=1}^{n} P_i}{P_0} \tag{2}$$

where P_0 is the power of transmitter after impedance matching, P_i is the power of all users.

According to (2), it can be concluded that the ECR will increase if there is illegal user in system. The effects of changes in frequency and coil quality factor on ECR are also considered. By measuring ECR continuously for 6 times and detecting whether there are suddenly changes, it can be used to judge the presence of illegal user or not. And, when the ECR becomes minimum, it can be considered that there is no illegal user.

And the decouple process is as follows: first, the system judge whether the ECR is close to minimum at the main operating frequency or not, if no, the transmitter and the legal users continue to hop until the ECR is close enough to the minimum. In extreme cases, if after consecutive frequency hopping for six times, the ECR is still relatively large, then the power will be cut off by MCU and alarm. The flow chart of identification and resonance decoupling method of single-multi mode as shown in Fig. 9.

IV. IMPLEMENTATION OF THE PROPOSED WPT IDENTIFICATION AND RESONANCE DECOUPLING SYSTEM AND EXPERIMENTAL RESULTS

As shown in Fig. 10, the proposed identification and resonance decoupling system is realized. There are four cases:

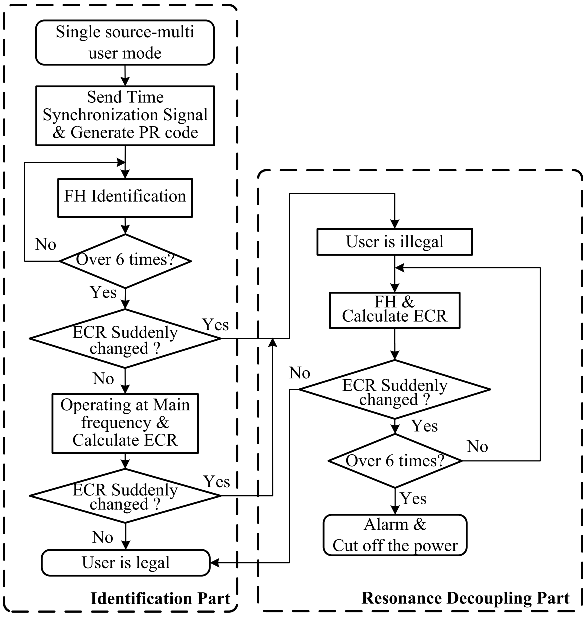


FIGURE 9. **The flow chart of identification and resonance decoupling method of single-multi mode.**

single-single mode with legal user (Fig. 10(a)), single-single mode with illegal user (Fig. 10(b)), single-multi mode with one illegal user (Fig. 10(c)) and single-multi mode with two illegal users (Fig. 10(d)). The power transfer distances of the single-single mode is set to 30cm, and the power transfer distances of the single-multi mode is set to 40cm. The parameters of the coils are shown in Table 1, and all of the coils are planar spiral type.

A. IDENTIFICATION EXPERIMENT IN SINGLE-SINGLE MODE

In our experiment, the legal user can work normally as shown in Fig. 10(a); for illegal user, the load cannot receive power as shown in Fig. 10(b).

In the experiment, the FH sequence and power of legal users has been tested for three times, as shown in Fig. 11. The experimental results are shown in Table 2, where the FH row represents the frequency after hopping, which is as same the order shown as Fig. 11, and the row below it represents the PTE after every hopping.

In Table 2, PR code has a relatively strong randomness, which shows that the proposed method is effective. The impact of variation of frequency and coil quality factor may cause slight fluctuations to PTE. The relay used in the experiment is HF49FD with very low power dissipation, and it could cause slight fluctuations in PTE. Based on the above considerations, the standard EFR is set to ±10% by this paper. And according to (3), the efficiency fluctuation rate (EFR) is from -3.6% to $+3.6\%$, which shows that this method has little effect on PTE.

$$EFR = \frac{PTE - Ave(PTE)}{Ave(PTE)} \tag{3}$$

TABLE 1. Parameters of resonant coils.

Radius of Wire	Coil Diameter	External Coil Diameter	Number of Turns	Spaces between Turns	Inductance	Capacitance	Resonant Frequency
2.12 mm	60 mm	300 mm	9	15 mm	20 μH	30 pF	6.78 MHz

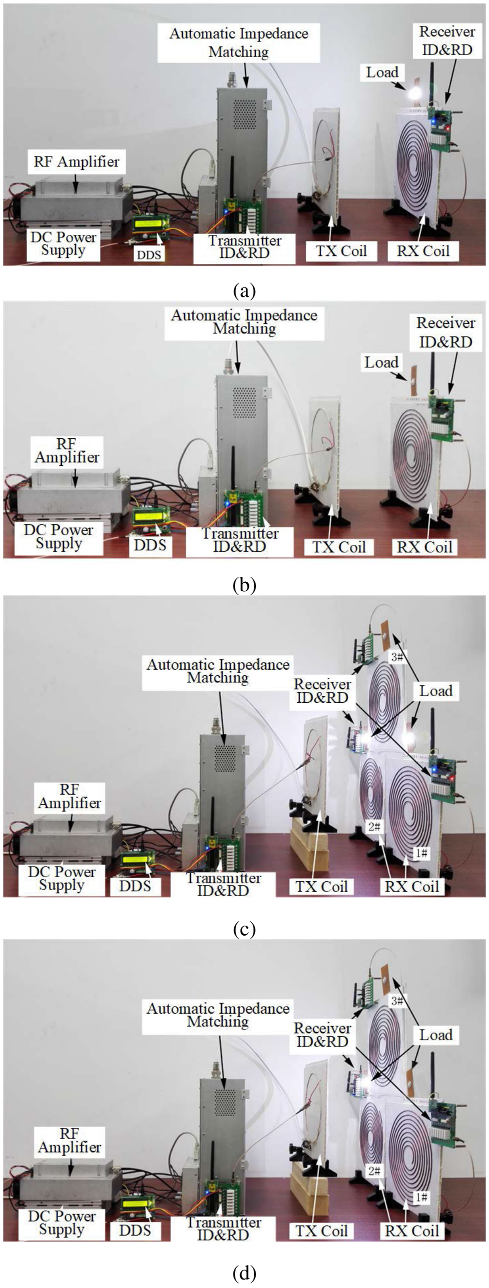


FIGURE 10. Experiment of identification and resonance decoupling. (a) Single-single mode (legal user). (b) Single-single mode (illegal user). (c) Single-multi mode (one illegal).(d) Single-multi mode (two illegal).

where the $Ave(PTE)$ denotes the average of 6 measured PTE values.

And the voltage and current of load the process of identification has been monitored, which shows that the voltage and current are relatively stable in the whole process, as shown in Fig. 12.

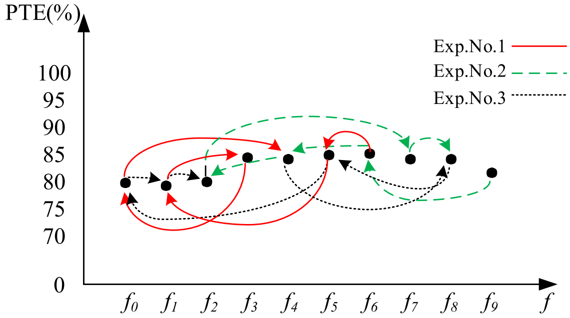


FIGURE 11. PR code sequence and PTE in single-single mode.

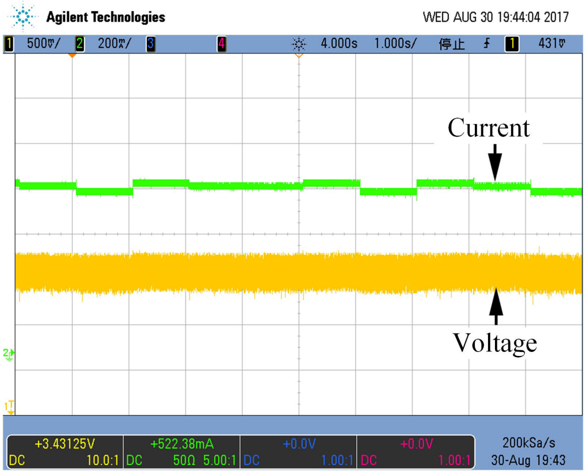


FIGURE 12. Monitoring data of load in single-single mode.

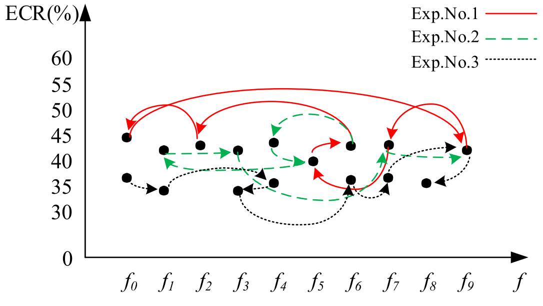


FIGURE 13. PR code sequence and PTE in single-multi mode.

B. IDENTIFICATION EXPERIMENT IN SINGLE-MULTI MODE

In the experiment, the load can work properly in the presence of an illegal user or two illegal users, as shown in Fig. 10(c) and Fig. 10(d). To illustrate the effectiveness of the method, the tests are repeated many times, and the results show that illegal user's power supply can be cut off.

TABLE 2. Experimental FH & PTE sequence in single-single mode.

	Type	FH & PTE Sequence	EFR
Exp. No.1	FH	f_6(4.94MHz)-f_5(4.85MHz)-f_1(4.34MHz)-f_3(4.68MHz)-f_0(4.16MHz)-f_4(4.72MHz)	-3.6% to 2.8%
	PTE	f_6(84.6%)-f_5(85.2%)-f_1(79.9%)-f_3(84.0%)-f_0(80.0%)-f_4(83.5%)	
Exp. No.2	FH	f_9(6.78MHz)-f_6(4.84MHz)-f_4(4.72MHz)-f_2(4.55MHz)-f_7(5.06MHz)-f_8(5.11MHz)	-2.3% to 2.1%
	PTE	f_9(81.0%)-f_6(84.6%)-f_4(83.5%)-f_2(81.3%)-f_7(83.3%)-f_8(83.6%)	
Exp. No.3	FH	f_4(4.72MHz)-f_8(5.11MHz)-f_5(4.85MHz)-f_0(4.16MHz)-f_1(4.34MHz)-f_2(4.55MHz)	-2.9% to 3.6%
	PTE	f_4(83.5%)-f_8(83.6%)-f_5(85.2%)-f_0(80.0%)-f_1(79.9%)-f_2(81.3%)	

TABLE 3. Experimental FH & PTE sequence in single-multi mode.

	Type	FH & ECR Sequence	ECRFR
Exp. No.1	FH	f_9(6.78MHz)-f_7(5.06MHz)-f_5(5.85MHz)-f_6(4.94MHz)-f_2(4.55MHz)-f_0(4.16MHz)-f_9(6.78MHz)	+8.7%
	ECR	f_9(43.8%)-f_7(43.2%)-f_5(41.4%)-f_6(44.0%)-f_2(44.5%)-f_0(45.0%)-f_9(43.8%)	
Exp. No.2	FH	f_6(4.94MHz)-f_4(4.72MHz)-f_5(4.85MHz)-f_1(4.34MHz)-f_3(4.68MHz)-f_7(5.06MHz)-f_9(6.78MHz)	+6.3%
	ECR	f_6(43.2%)-f_4(44.0%)-f_5(41.4%)-f_1(43.8%)-f_3(43.5%)-f_7(43.2%)-f_9(43.8%)	
Exp. No.3	FH	f_0(4.16MHz)-f_1(4.34MHz)-f_4(4.72MHz)-f_3(4.68MHz)-f_6(4.94MHz)-f_7(5.06MHz)-f_9(6.78MHz)-f_8(5.11MHz)	+28.8%
	ECR	f_0(37.1%)-f_1(34.0%)-f_4(35.5%)-f_3(34.0%)-f_6(36.2%)-f_7(37.5%)-f_9(43.8)-f_8(36.2)	
Exp. No.4	FH	f_6(4.94MHz)-f_5(4.85MHz)-f_1(4.34MHz)-f_3(4.68MHz)-f_9(6.78MHz)-f_7(5.06MHz)	+144.8%
	ECR	f_6(22.6%)-f_5(21.9%)-f_1(22.3%)-f_3(22.1%)-f_9(53.6%)-f_7(22.5%)	
Exp. No.5	FH	f_9(6.78MHz)-f_3(4.68MHz)-f_7(5.06MHz)-f_1(4.34MHz)-f_0(4.16MHz)-f_8(5.11MHz)	+61.7%
	ECR	f_9(23.4%)-f_3(22.9%)-f_7(35.4%)-f_1(23.1%)-f_0(36.7%)-f_8(22.7%)	

Next, the FH sequence of users has been tested for three times, the first two times were all legal, there was an illegal in the third time, as shown in Fig. 13. It can be seen from the experimental results as shown in Tab. 3, that PR code has a relatively strong randomness. The fourth and fifth tests set two illegal users, the fourth test set two illegal users with the same frequency, and the fifth test set two illegal users with different frequencies. The experimental results are also shown in Tab. 3. According to (4), the fluctuation rate of ECRFR of results are presented as well.

Considering the impact of variation of frequency and coil quality factor and relay power consumption can cause slight fluctuations to PTE, the standard ECRFR is set to ±10% by this paper. The ECRFR of Exp. No.1 and 2, which are all legal users, are less than 10%. For the last three test experiments, the ECRFR is more than 10%, so it can be judged that there are illegal users, and also shows the effectiveness of the proposed method. After that, the system decouples the illegal users and ECRFE returns to less than 10%.

$$ECRFR = \frac{Max(PTE) - Min(PTE)}{Min(PTE)} \tag{4}$$

V. CONCLUSION

To solve the problem of electricity theft in WPT, an identification and resonance decoupling method based on FH communication is proposed. Single-single and single-multi modes were discussed separately. An experimental system is implemented, and a good agreement between the measurements and theoretical analysis is obtained. It is noteworthy that the identification and resonance decoupling process has no adverse effect on the power supply of legal users. Moreover, in order to improve the reliability of the method, we use the pseudo-random code to control the frequency.

Although increasing the number of hopping frequencies can improve the accuracy of identification, the complexity and cost of equipment will also increase accordingly, so the number need to be considered as appropriate in practical applications. The method presented in this paper contributes to the practical application of WPT system.

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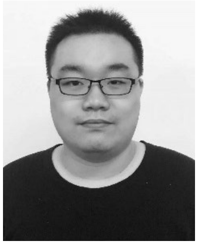

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