A new method of encryption wireless energy transmission for EV in the smart grid

Li Ji, Lifang Wang and Chenglin Liao

Abstract—Wireless charging has played a crucial role in electric vehicle charging market presently. As electric vehicles will be important nodes access to the smart grid in the future, the security flow of energy and information between wireless charging infrastructure and the smart grid will directly affect the security of the smart grid. A novel secure wireless transfer method for energy and information transfer simultaneously has been represented in this paper by designing a reasonable dual-band coil for simultaneous transmission of energy and information, using improved chaotic modulation and a three times handshake protocol for encrypting energy and information between wireless charging infrastructure and the smart grid. Both the simulation and experiments show that the security of energy transmission can be effectively improved by this structure, in the premise of ensuring the power and efficiency of wireless energy transmission.

Index Terms—Chaotic modulation, dual-band coil, secure wireless energy transfer strategy, smart grid.

I. INTRODUCTION

As the penetration rate of EVs (Electric Vehicles) into the transportation fleet accelerates, EVs works not only as loads, but also as energy storage resources for the smart grid [1]. In recent years, the emerging wireless power transmission (WPT) technology shows promising potential for EVs. The WPT system can be utilized to provide wireless charging for EVs located in inaccessible positions. Additionally, it shows great potential to perform emerging energy exchange among EVs or between EVs and the smart grid. The relationship between the smart grid and wireless charging EVs load is shown in Fig. 1.

Fruitful achievements on the working principle, circuit topology, and transfer efficiency of various WPT systems have been made [2]. But energy is transferred without any safety control currently. The application of the WPT technique is limited since the security issue is nearly unexplored [3]. Chaos theory has been successfully applied to various applications, and the chaotic encryption has been widely used for secure telecommunication [4]. Zhen Zheng et al. [2, 3] provided a new method of encryption for wireless power transfer by using a single channel. Firstly, As described in the paper, the frequency of the power side is proportional to the energy transfer efficiency, which will be certainly affected if transmission of energy is encrypt by this way, especially in the case of large air gap transmission of high frequency. Secondly, this approach requires changing the capacitance continuously, which is actually completed by switching capacitor array. Thus electrical noise and energy loss will be greatly increased and this is very difficult to control. Several methods have been proposed to transfer safety information and power in the same inductive link [5-8]. For example, in some low power cases, the inherent inductive link for power transfer is exploited as an antenna for data transmission, where the data is directly modulated on the power carrier. However, the techniques that employ a single carrier for both power and data transfers have two major drawbacks. The first one is that the data rate is limited by the frequency of the carrier. The second drawback is that the technique used for forward communication decreases the power transmission efficiency since the operation of system shifts from its optimal points, which will inevitably lead to power and energy transfer efficiency loss. In this paper, a reasonable design of dual-band system for simultaneous transmission energy and information is proposed, and the bandwidth for the information transfer is presented and analyzed. By this method, the energy transmission power and efficiency are guaranteed, and the bandwidth of the information transmission can be improved as much as possible. According to the method, the energy from the smart grid to a EV is encrypt by a 500 W energy transmission and 31.2 kbps information transmission prototype system using chaos encryption algorithm and a three times handshake protocol.

The rest of this paper is organized as follows. Dual-band MRC-based WPT system will be analyzed in section II, and the
methodology of the proposed energy encryption method will be presented in section III. In Section IV, both simulation and experimental results will be given to illustrate the validity of the proposed method. Finally, conclusions will be drawn in Section V.

II. ANALYSIS OF DUAL-BAND MRC-BASED WPT SYSTEM

MRC is a type of electromagnetic induction with high efficiency and longer transmission distance compared to the magnetic induction method [9-11].

The architecture of WPT system for EV from the smart grid is shown in Fig. 2 and the equivalent circuit model of Fig. 2 as shown in Fig. 3.

Fig. 2. Architecture of WPT system for EV.

![Architecture of WPT system for EV](image)

Fig. 3. Equivalent circuit model of WPT system for EV.

According to Kirchhoff’s law, the equivalent circuit will satisfy the following matrix equation:

\[
\begin{bmatrix}
U_1 \\
0
\end{bmatrix} =
\begin{bmatrix}
Z_1 & jwM_{12} \\
jwM_{12} & Z_2
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix}
\]

\[
Z_1 = R_1 + jwL_1 + 1/jwC_1
\]

\[
Z_2 = R_2 + jwL_2 + 1/jwC_2 + R_c
\]

\[Z_1\] represents the impedance of energy sender side, and \[Z_2\] represents the impedance of energy receiver side. It can be deduced that the maximum efficiency from the energy sender side to receiver side is proportional to \[k_{12}Q_1, Q_2\], and \[Q_2\] respectively.

\[\eta_{max} = \frac{t}{(1+t+1)}, \quad t = k_{12}Q_1Q_2\]


define the input power is \[U_s = U_s \cos \omega t\]

The quality factor \(Q\) of above circuit when it works in series resonant frequencies can be described as [15]:

\[
Q_1 = \frac{\omega_1}{R} (L_s + L_p) \left(1 - \frac{\omega_a^2}{\omega_1^2}\right)
\]

\[
Q_2 = \frac{\omega_2}{R} (L_s + L_p) \left(1 - \frac{\omega_s^2}{\omega_2^2}\right)
\]

\[\omega_a\] is the resonant frequency by \[L_a\] and \[C_a\]. According to the definition of the bandwidth, the bandwidth of the resonant frequency \[\omega_s\] is as follow:

\[
B_W = \frac{\omega_2}{2\pi Q_2} = \frac{R}{2\pi(L_s + L_p) \left(1 - \frac{\omega_s^2}{\omega_p^2}\right)}
\]

Pictured the relationship between \[1/(1 - (\omega_s^2/\omega_p^2))\] with \[\omega_s/\omega_p\] in Fig. 5.

![Relationship between 1/(1-(\omega_s^2/\omega_p^2)) with \omega_s/\omega_p](image)
As is shown in Fig. 5, when the $\omega_2 / \omega_p$ is bigger than 3, the denominator of the $B_w$ will get the minimum value and the bandwidth will get the maximum value, that is $R/2\pi L$. In order to increase the bandwidth of $\omega_2$, the inductance value of $L_s$ need to be designed as small as possible.

From above analyze, to maximize the bandwidth of $\omega_2$, the restrictions between the circuit parameters is:

\[
\begin{align*}
L_p C_s + L_s C_p + L_p C_p + \sqrt{(L_p C_s + L_s C_p + L_p C_p)^2 - 4L_s C_s L_p C_p} > 3 \\
L_s & \text{ is as small as possible} \\
(L_p C_s + L_s C_p + L_p C_p)^2 - 4L_s C_s L_p C_p > 0
\end{align*}
\]

The relationship between the $L/L_p$ and the $C_s/C_p$ can be deduced by solving this equation as:

\[
9 - \frac{L_s}{L_p} + 8 \frac{L_s}{C_s} > 72
\]

III. ENERGY ENCRYPTION METHOD

From the analysis of above, the dual-band MRC based WPT system for EV can provide enough bandwidth for secure communication between the smart grid side and the EV side. However, there is no denying that high frequency inverter switch is indispensable to make the coil in the state of high frequency. Even though we choose class E amplifier as the inverter circuit, which has just one switch tube, high frequency switch will also bring much noise to information transmission channel. Because the energy requirement is time-varying and uncertain, the switch noise is nondeterministic white noise. In order to against the switch noise, the chaos modulation is adopted to enhance the security and robustness of information transmission [16].

As chaotic signals are irregular, a periodic, uncorrelated, broad band, easy to generate, and difficult to predict over a long time, the secure communication based on these inherent features of a chaotic signal has aroused ongoing and growing research interest [16]. Using chaos theory and dual-band wireless energy transmission infrastructure, a high-frequency information transmission channel is allowed to be used to transmit chaos encrypt information to control the energy transmission in the low-frequency channel, thus to achieve wireless energy security transfer between electric vehicles and the smart grid. Chaotic systems are deterministic systems, which present random characteristics. It is a very good means of communication encryption because it is resistive to attack and easy to demodulate. And it is also very suitable for the nondeterministic white noise communication channel. In the present study, the improved Logistic chaotic sequence mapping to encrypt energy was adopted by using chaotic modulation.

Definition of the improved Logistic chaotic sequence mapping is:

\[
X'_{(n+1)} = 1 - M \cdot X^2(n) \quad r \in [0,2], \quad x \in [-1,1]
\]

The range of $r$ is $[0, 2]$, the range of $X(n)$ is $[-1,1]$, the coefficient $M$ selection will determine whether the system is in a chaotic state, as shown in Fig. 6:

![Fig. 6. Improved Logistic chaotic sequence mapping diagram.](image)

Apparently, system will be in chaotic status when $1.41>M>2$. The transmitted signal is $S_n$, $S_n=0, 1, 2, ..., n=0,1$. Modulating the logistic mapping parameters $a$ as follows

\[
M(a) = \begin{cases} 1.48, & S(a) = 0 \\ 2, & S(a) = 1 \end{cases}
\]

The initial value of $X_0$ is $0.5<X_0<1$. Then, the transmitted information $X_{(n)}$ was included and define

\[
X'_{(n+1)} = 1 - M(a) \cdot X^2(n) \quad r \in [0,2], \quad x \in [-1,1]
\]

And performs threshold processing to $X(n)$ and let $|X(n)| > 0$

\[
\begin{align*}
X_{(n)} &= \begin{cases} X'_{(n)} + 0.5 & 0 \leq X'_{(n)} < 0.5 \\ X'_{(n)} - 0.5 & -0.5 \leq X'_{(n)} < 0 \\ X'_{(n)} & \text{other} \end{cases} \\
Y_{(n)} &= \begin{cases} X'_{(n)} + 0.5 & 0 \leq X'_{(n)} < 0.5 \\ X'_{(n)} - 0.5 & -0.5 \leq X'_{(n)} < 0 \\ X'_{(n)} & \text{other} \end{cases}
\end{align*}
\]

It can be derived that $Y_{(n)}=X_{(n)}$. At the receiver side, the equation can be expressed as follow

\[
Z_{(n)} = 1 - M(a) \cdot Y^2(n)
\]

When comparing the $Z_{(n)}$ and the next receive signal $X'_{(n+1)}$, it can be obtained that

\[
Z_{(n)} - X'_{(n+1)} = [M(a) - M(a)] \cdot X^2(n)
\]

The receive signal is

\[
S'_{(n)} = \begin{cases} 0, & [Z_{(n)} - X'_{(n+1)}] < 0 \\ 1, & [Z_{(n)} - X'_{(n+1)}] > 0 \end{cases}
\]

Therefore, by adopting the method of dual band structure and chaos modulation, the information and energy can be transferred at the same time. By changing the map parameter
$M_{ij}$, the signal transmission bandwidth can be regulated. And thus the safety of energy transmission can be controlled by communication means. In the next step, how to use communication means in the second band to control the energy transmission in the first band will be discussed.

In order to achieve the control of the energy transmission, either the energy sender or receiver side need to make certification. And both sides can transfer energy and information only if they certificate successfully, otherwise they can’t exchange energy and information for each other. Through this way, the safety of the energy transmission can be guaranteed and the waste of power can also be avoided, thus increase the use of energy efficiency. Control procedures using this secure wireless energy transfer strategy between the sender and receiver side is shown in Fig. 7.

Detailed process is described as following steps:

1. The first step (the first handshake): Establish a connection, the EV side enter the SYNSENT state after sending syn packets to the smart grid side, waiting for the confirm information from the smart grid side.
2. The second step (the second handshake): Smart grid side receives syn packets, and confirm the customer SYN, and send a SYN packet, that is, SYN + ACK packet, then the smart grid side go into SYNRECV state;
3. The third step (the third handshake): The EV side receives SYN + ACK packet from the smart grid side, and sends a confirmation packet to the smart grid side. After this package has been sent, both of the two sides turn into the ESTABLISHED state. Now, the certification Process is completed.

Through this three times handshake, EV side and the smart grid side can be confirmed by each other and any energy and information requirement would be exchanged freely. The energy loss can only be in the process of authentication, which is so tiny that can be neglected because of low voltage and little time in this process.

### IV. PERFORMANCE ANALYSIS BY SIMULATION AND EXPERIMENT GUIDELINES FOR MANUSCRIPT PREPARATION

In order to produce dual-band MRC based WPT structure, 500 kHz was choose as the system operating frequency. The measured parameters of this system are listed in Table I. Parameters in Table I are used in the simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_p$</td>
<td>74.4μH</td>
</tr>
<tr>
<td>$C_p$</td>
<td>1.36nF</td>
</tr>
<tr>
<td>$L_s$</td>
<td>1.8μH</td>
</tr>
<tr>
<td>$C_s$</td>
<td>0.95nF</td>
</tr>
<tr>
<td>$d$</td>
<td>20cm</td>
</tr>
<tr>
<td>$M_{12}$</td>
<td>11.4μH</td>
</tr>
</tbody>
</table>

Using Matlab to simulate the system resistance feature, the simulation results are shown in Fig. 8.

![Impedance of the dual-band coil](image)

Fig. 8. Impedance of the dual-band coil.

It can be seen that the simulation is consistent with the former analysis, which means this circuit structure can produce two series resonance making the coil impedance is 0. So it can be used to transmit energy and information in different frequency simultaneously.

A spiral coil of square shape two coil EV oriented wireless charging prototype was adopted to demonstrate the validity of the presented design architecture and communication method. Outside coil winding length is 400mm, the space of each coil wire is about 13mm, wireless energy transmission distance is 200mm, and the coil made of 4.8mm diameter wire wound from Leeds. The send coil and the receive coil are shown in Fig. 9.

![The send coil and the receive coil](image)

Fig. 9. The send coil and the receive coil.

The network analyzer (Agilent E5061B) was used to get the resonance frequency diagram in 500 kHz, the results are shown in Fig. 10.
Fig. 10. The $S_2$ parameter of the dual-band.

Obviously, the system has two resonant frequency: the lower frequency channel can be used for wireless energy transfer and the higher frequency channel can be used for information transmission within the bandwidth range.

By using the second resonance frequency which is 1 M energy transmission in encrypted channel, and chaotic modulation signal generating strategies generated by Freescale MPC5674F, after adding a signal amplifier transformer coupled to the dual-band MRC based coil, the signal waveform of the sender and the receiver are shown in Fig. 11.

Fig. 11. Experimental results of simultaneous wireless power and information transmission.

From Fig. 11, it can be seen that the signal is easy to demodulate, and the maximum signal transmission bandwidth can reach 80 kHz, and the max bandwidth is 83.4 kHz, which is near to the theoretical analysis in equation (22). The experimental results show that the bandwidth of the aforementioned chaotic encryption algorithm in section 2 is about 40 kHz when the receive logistics map parameter $M(r) = 1.74$. So the coil bandwidth is sufficient to transmit this encryption algorithm.

The software Comsol, a multi-physics coupling simulation tool, was applied to simulate the coil magnetic field lines distribution after both successful and failure handshake. The result is shown in Fig. 12.

As can be seen from Fig. 12, the magnetic lines distribute nearly fully between the two coils when the sender and the receiver authentication are successful. Energy and information can be transmitted even if authentication fails, or almost no magnetic lines between the two coils, which means there would be no energy transferred.

After successful handshake, the first resonance frequency of the channel (500k) can be used to transfer energy. With the driven voltage is DC 300V, the receiver side can get 2.75 kW energy, and the energy transfer efficiency can reach 93%.

Both theory analysis and experimental verification demonstrated that the energy in the encrypted channel to transmit information can be transmitted safely and efficiently.

V. CONCLUSION

To complete safe and efficient wireless energy and information transmission between the smart grid and EVs, the double-band MRC based on WPT structure and chaotic modulation technology were combined in the present study. After analyzing the contradictory requirements of the coil structure for wireless energy transfer and information transmission, adding tiny capacitance or inductance to get enough bandwidth of the second band to support the communication need. Its validity has been verified by both theoretical analysis and experimental results. However, this kind of dual-band MRC based on WPT system is different from other single-band system. That is, nondeterministic white noise can be brought by energy transfer switch from the first band to the second one. So a chaotic modulation method was included to improve the security and robustness of information transmission. Improved Logistic mapping parameters 1.48 and 2 were used respectively to modulate signal 0 and 1, and demodulation parameter is 1.74, which allowed the encrypted signals to combat channel interference. Throwing the three times handshake procedure, the smart grid side and the EV side can be authenticated by each other to ensure the safety of energy transmission. Finally, a set of coil structure and a wireless energy and information transmission system have been designed in this study. The wireless transmission power is 100 W, efficiency is 90% and information transmission speed is 200 kbps, and the coil bandwidth is sufficient to transmit the encryption algorithm, which well verified the effectiveness of the proposed strategy.

REFERENCES


**Chenglin Liao** (M’09) received the Ph.D degree in Power Machinery and Engineering from Beijing Institute of Technology, Beijing, China, in 2001. After that he had spent 2 years as a postdoctoral researcher with Tsinghua University. He is currently the deputy director of Department of Vehicle Energy System and Control Technology, Institute of Electrical Engineering, Chinese Academy of Sciences. For the past 9 years at Institute of Electrical Engineering, he had been involved in research on battery management systems, vehicle control and wireless charging systems for electric vehicles. His currently research work is mainly concerned with the development of high power wireless charging system for commercial Electric Vehicles.

**Li Ji** is currently working in the Institute of Electrical Engineering (IEE), Chinese Academy of Sciences. Her research interests includes: wireless power transfer theory, simultaneous transmission power and information technology, and design and optimization of EV oriented wireless charging systems.

**Lifang Wang** received the Ph.D degree in 1997 from Jilin University. After that she joined the Institute of Electrical Engineering (IEE), Chinese Academy of Sciences. During the Chinese tenth-five year plan(2001-2005), she was a member of the national specialist group of Key Special Electric Vehicle Project of the National 863 Program, and she was the Head of the 863 Special EV Project Office. She is currently the director of Department of Vehicle Energy System and Control Technology at IEE. She is also the vice director of Key Laboratory of Power Electronics and Electric Drive, Chinese Academy of Sciences. Her research interests include Electric Vehicle control systems, EV battery management systems, wireless charging systems for EV, electromagnetic compatibility and smart electricity use. She has directed more than 15 projects in these fields and has published more than 60 papers and 30 patents.

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