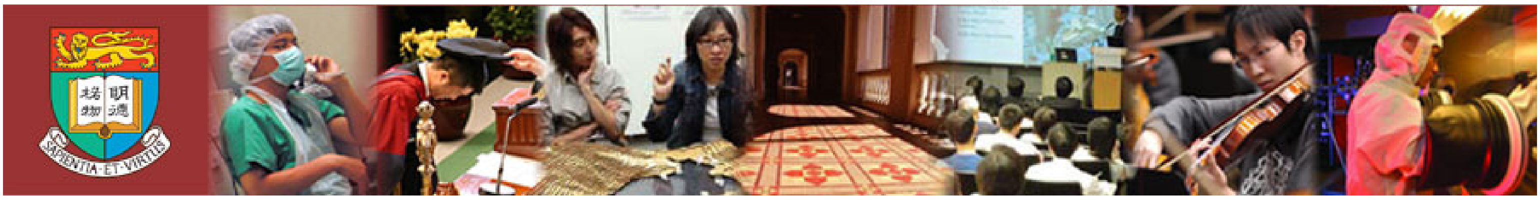

Energy-Security-Based Contactless Battery Charging System for Roadway-Powered Electric Vehicles

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***Abstract*—This paper proposes an encrypted contactless charging system for roadway-powered electric vehicles (EVs), where the energy can be specifically transferred from the electric supply to authorized EVs. The key of the proposed energy encryption scheme is to utilize the random-like Gaussian map as the security key to chaotically regulate the charging circuit of the electric supply. In such way, the energy can be wirelessly transferred to authorized EVs, while unauthorized EVs cannot illegally acquire the electric energy without knowledge of the security key. Hence, the proposed energy encryption scheme can significantly improve the secure performance of the roadway EV charging system. In this paper, the simulated and experimental results are both provided to illustrate the effectiveness of the proposed the encrypted contactless charging system for multiple roadway-powered EVs.**

***Keywords*—Energy security; electric vehicle; wireless power transfer**

I. INTRODUCTION

Roadway-powered electric vehicles (EVs) have attracted increasing attentions from industrial engineers and academic researchers in recent years [1], which not only possesses characteristics of conventional battery-powered EVs, but also overcomes limitations of the current battery technology, such as the battery capacity and charging time. Hence, the roadway powering mechanism can effectively improve the driving range of EVs, therefore showing significant meanings for renewable energies to penetrate into our daily life.

The concept of wireless power transfer (WPT) can be tracked back to more than 100 years ago as Nikola Tesla carried out his experiments on power transmission without wires in 1899 [2]. According to the transmission distance, the WPT can be classified into two groups: the far-field and near-field technologies. As the far-field technology is significantly affected by the topographical condition, it is ill-suited for electric vehicle (EV) application. Among various WPT mechanisms such as the inductive, capacitive and acoustic couplings of the near-field technology [3], the inductive power transfer has been identified to be most feasible for EV application [4], [5].

The WPT for EVs initially employed electromagnetic induction with ferrite cores to achieve strong coupling, but the air-gap was limited to several centimeters. Then, researchers made use of magnetic resonance to extend the air-gap length to tens of centimeters for EV charging [6]. With the introduction of multi-coil magnetic resonance coupling, the air-gap was further extended to several meters [7]. Consequently, a WPT system was proposed for multiple small receivers [8], which formed a basis for charging multiple EVs. Then, a WPT system with a narrow rail width, a small pickup size and a large air-gap was developed for online EVs, allowing them to perform on-road charging [9]. By further optimizing the core structures and incorporating the power line segmentation, the online EV could pick up 100 kW with an efficiency over 80% at an air-gap of 26 cm [10]. Meanwhile, a bipolar DC system was proposed, which could enable each substation to supply power mutually to the online EVs and thus reduce the effect of drastic increase of power consumption [11]. Also, a dynamic wireless charging system was proposed for charging EVs, which employed the reactance reflected by the receiver to automatically increase the magnetic field strength in coupled portions for the improvement of power transfer efficiency [12]. Incorporating the vehicle-to-grid concept, a bidirectional power interface was developed to facilitate simultaneous charging and discharging of multiple EVs [13].

There were two main kinds of magnetic couplers for on-road charging of EVs. The first kind was a long track coupler with an adoption of U-type, W-type or I-type ferrite [9]. This track design suffered from the inflexibility of extension and relatively low coupling coefficient. By applying segmentation, the track became like a pad for stationary charging, which was the other kind of magnetic coupler for on-road charging [14]. Two single-sided flux pad couplers were developed for EVs, namely the circular unipolar pad and rectangular bipolar pad which was dubbed the DD pad [15]. By incorporating an additional quadrature coil named Q coil on the receiving pad, the DD-DDQ arrangement could provide the charging zone more than five times larger than that of the circular pad.

Different compensation topologies were developed depending on how the compensation capacitors were added to the sending and receiving coils, namely series-series, series-parallel, parallel-series and parallel-parallel topologies [6]. Among them, the series-series topology was widely adopted for EVs. Hence, with proper compensation network parameters, zero voltage switching could be ensured for all the primary switches [16]. Some other topologies were also proposed: for

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instance, by utilizing LCC compensation, a zero-current switching condition could be achieved [17]. Also, the double-sided LCC compensation network was developed to achieve zero-voltage switching for the primary switches [18].

There were various analytical approaches for formulating the power transfer efficiency, which could be categorized as the coupled-mode theory [19] and the circuit theory [20]. While both approaches could result in the same set of equations in steady state for short- or mid-range coupling [21], electrical engineers prefer to use the circuit model which can provide more information on the selection of circuit components. Meanwhile, by using the equivalent circuit and Neumann formula, the efficiency and air-gap length could be maximized [22]. Moreover, based on an equivalent circuit, a series-series compensated system was modeled using the extended describing function, which could provide the continuous-time small-signal model for both the frequency and phase-shift control [23].

In order to achieve the maximum power transfer, there were three main adaptive control strategies: the adaptive frequency tuning, adaptive impedance matching and adaptive rectification. For the adaptive frequency tuning, the controller automatically adjusted the operating frequency in such a way that the input impedance of the coils could match with the source impedance [24]. For the adaptive impedance matching, the source and load impedances were matched by using an automated impedance matching circuit which employed switched-capacitor arrays to realize the variable capacitors [25]. For the adaptive rectification, a feedforward buck converter was controlled to maintain optimal impedance matching between the receiver and the rectifier while the load was not constant [26].

However, the energy security issue has been nearly explored in WPT technologies [27]. This paper proposes a secure contactless charging system for roadway-powered EVs, where the charging circuit is chaotically regulated by utilizing the random-like security key to protect the wirelessly transferred energy in an encrypted transmission channel. In such way, the authorized EV can effectively receive the energy by using the acquired security key, and meanwhile the unauthorized EV can be successfully prevented from stealing the energy without knowledge of the security key.

The rest of this paper is organized as follows. Section II will present the proposed energy-security-based WPT technique, where both the mathematical analysis and corresponding implementation procedure will be discussed elaborately. In Section III, both simulation and experimental results will be provided to illustrate the feasibility of the proposed energy-security-based WPT scheme for roadway-powered EVs. Finally, conclusions will be drawn in Section IV.

II. Energy-Security-Based Scheme

In this paper, the proposed contactless charging system is fulfilled based the MRC-based WPT technique, which significantly depends on the switching frequency. Specifically speaking, the EV battery can be wirelessly charged under the optimal switching frequency, while the transferred power can be reduced at an insignificant level when the frequency deviates from the optimal value. Thus, the characteristic of the frequency sensitivity can be utilized to encrypt the transferred energy to improve the security performance of contactless charging system for roadway-powered EVs.

In order to regulate the switching frequency in a unpredictable way, the Gaussian map is utilized to generate the security key based on its random-like characteristics. The Gaussian map is a one-dimensional nonlinear iterated map, which is given by [7]:

$$x_{n+1} = \exp(-\alpha x_n^2) + \beta \tag{1}$$

where α is the parameter to regulate the magnitude of chaotic oscillation and β is the bifurcation parameter. Fig. 1 shows the bifurcation diagram when α equals 6.2, where the sequence x_n performs the chaotic oscillation within (–0.3, 0.7) when β varies from –0.7 to –0.3. Accordingly, the switching frequency ω can be chaotically regulated within ($0.5\omega_0$, $1.5\omega_0$) by utilizing the security key μ which is given by:

$$\omega = \mu\omega_0 \tag{2}$$

where ω_0 is the optimal frequency and μ can be obtained according to ($0.8+ x_n$).

Fig. 2 depicts the series-series topology of the MRC-based contactless charging system for roadway-powered EVs, which consists of individual units. It shows that each unit mainly has three parts, including the power supply unit, magnetic resonant unit and receiver unit. For authorized EVs, by simultanously regulated the capacitance with the acquired security key, the whole charging circuit can work in the resonant state to achieve the maximum transferred power, which is expressed as:

$$\begin{aligned} \omega_0 &= \frac{1}{\sqrt{L_p C_p}} \\ &= \frac{1}{\sqrt{L_{r1} C_{r1}}} = \frac{1}{\sqrt{L_{s1} C_{s1}}} = \cdots = \frac{1}{\sqrt{L_{rn} C_{rn}}} = \frac{1}{\sqrt{L_{sn} C_{sn}}} \end{aligned} \tag{3}$$

For unauthorized EVs, without knowledge of the security key, the value of LC cannot match with the encrypted switching frequency. Consequently, the transferred power can be reduced in an insignificant level, therefore effectively avoiding unauthorized EVs to illegally obtain the energy from the contactless roadway charging system.

Fig. 3 graphically demonstrate the entire procedure of the proposed encrypted contactless charging system for roadway-powered EVs. In the power supply unit, the switching frequency is chaotically regulated by utilizing the Gaussian-map-generated security key, which performs random-like variation and is thus unpredictable for all energy receiver units. In such way, the power supply unit works in the standby state to response the charging request from EVs. For charging requests, the EV identification is firstly verified by the power supply unit. The request from unpaid, unstable or illegal EVs are rejected, and corresponding vehicles are categorized to the unauthorized group to prevent from accessing the contactless roadway charging system. For authorized vehicles, the power

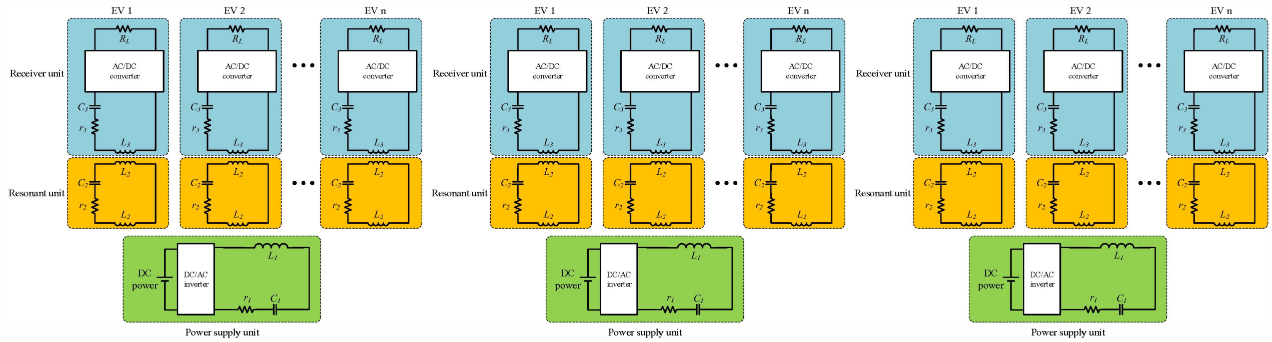


Fig. 2. Circuit diagram of MRC-based contactless EV charging system.

supply unit accepts the charging request and then delivers the security key to corresponding EVs. Then, the resonant and receiver capacitors can be simultaneously regulated by utilizing the acquiring the security key, which is given by:

$$C_2 = \frac{1}{\mu^2} \cdot \frac{1}{\omega_0^2 L_2} \tag{4}$$

$$C_3 = \frac{1}{\mu^2} \cdot \frac{1}{\omega_0^2 L_3} \tag{5}$$

Then, the wirelessly power transmission system can achieve the maximum transferred power to effectively charging authorized EVs. Consequently, the proposed contactless roadway charging system can encrypt the wirelessly transferred energy, therefore significantly improving the security performance.

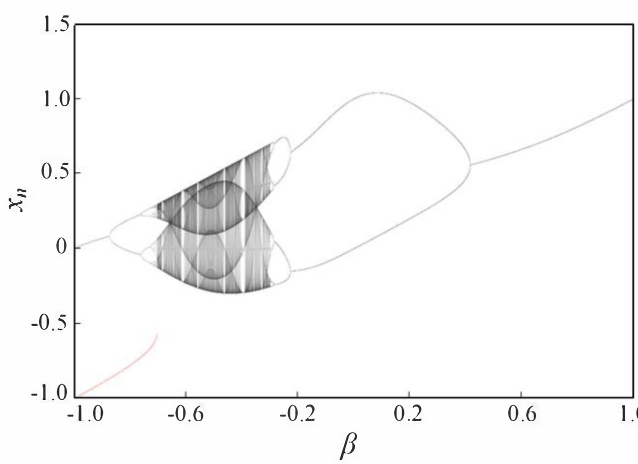


Fig. 1. Bifurcation diagram of Gaussian map.

III. VERFICATIONS

A. Simulation Results

To validate the proposed contactless EV charging system, the electromagnetic field analysis is carried out by using JMAG. The system simulation is conducted by using MATLAB/SIMULINK. The key parameters of the MRC-based charging system are listed in Table I.

In this paper, a downscale simulation model is set up to illustrate the proposed energy encryption scheme for roadway contactless EV charging systems, which mainly comprises one power supply unit to represent the roadway contactless charging system and two receiver units to represent roadway-powered EVs, namely EV-A and EV-B. In the case study, EV-A is authorized to access the roadway contactless charging system in two different durations, namely from 0.1 s to 0.3 s and from 0.4 s to 0.5 s, while EV-B is authorized to be charged from 0.2 s to 0.4 s. The downscale computational simulation is carried out to illustrate how the proposed roadway contactless charging system deals with charging requests from multiple EVs. In addition, by switching on and off specific parallel-connected capacitors, the capacitance regulation can be realized as (4) and (5). The parameters of capacitor arrays are listed in Table II.

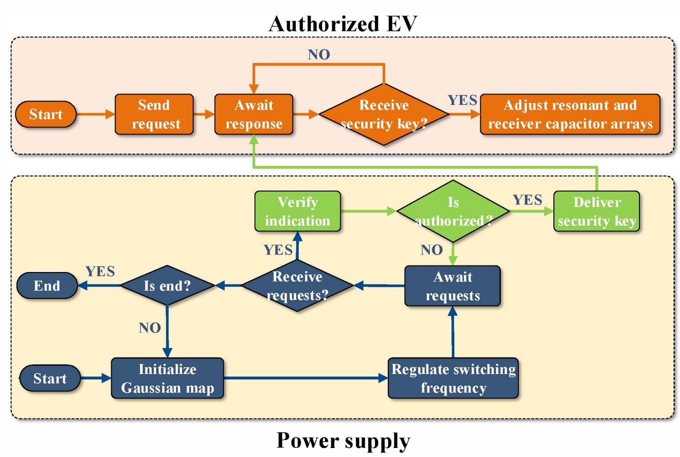


Fig. 3. Flowchart of the proposed contactless EV charging system.

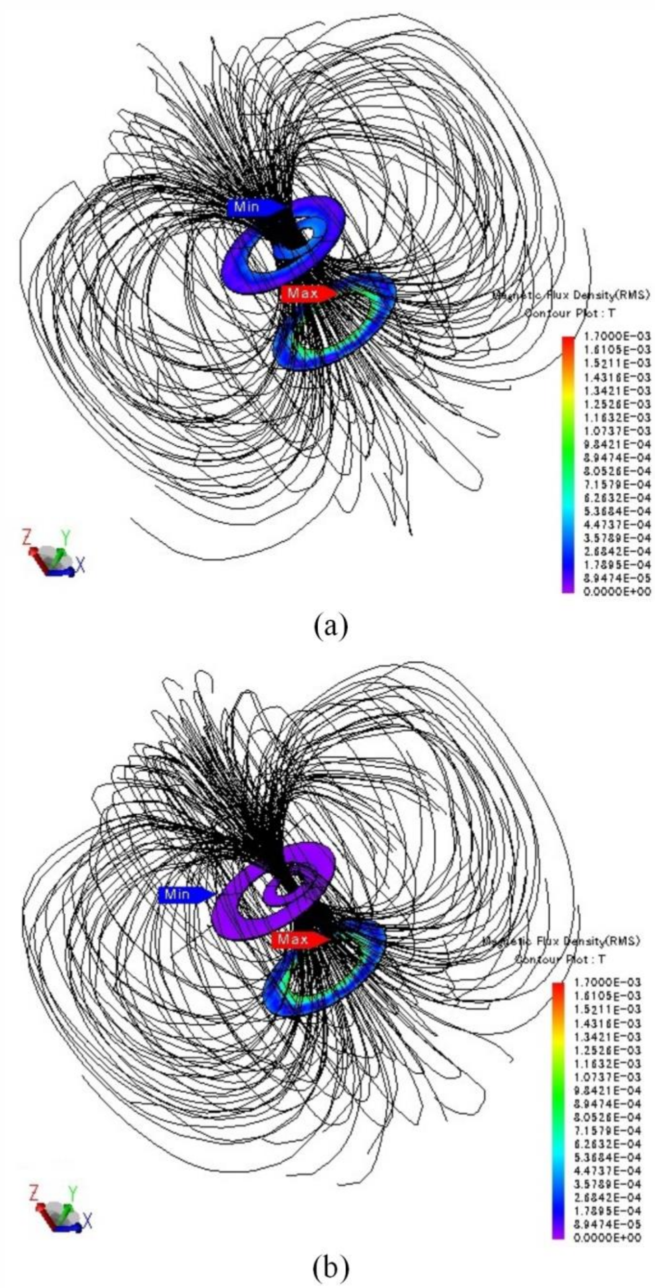


Fig. 4. Electromagnetic field analysis: (a) authorized EV; (b) unauthorized EV.

Fig. 4 shows the electromagnetic field analysis for authorized and unauthorized EVs, respectively. It illustrates that the magnetic flux density of the resonant and receiver coils can reach around 0.25 mT for charging authorized EVs, while the magnetic flux density drastically reduces to approximate 0 mT for unauthorized EVs. Fig. 5 and Fig. 6 depicts the charging voltage and current of EV-A and EV-B, respectively. It shows that EV-A can effectively obtain the charging voltage of 10 V and the charging current of 1 A from 0.1 s to 0.3 s and 0.4 s to 0.5 s. When EV-A is unauthorized to access the roadway contactless charging system, the corresponding charging voltage is drastically reduced to around 0.25 V and the charging current is also reduced to around 0.05 A. Meanwhile, EV-B can be also successfully obtain the wirelessly transferred energy from the roadway charging system at expected power level during 0.2 s to 0.4 s. Additionally, the energy transmission channel can be also successfully turned off for EV-B in the rest test time. Therefore, the proposed roadway contactless charging system can effectively transfer the energy to the authorized EVs and meanwhile prevent unauthorized EVs from accessing the wirelessly transferred energy.

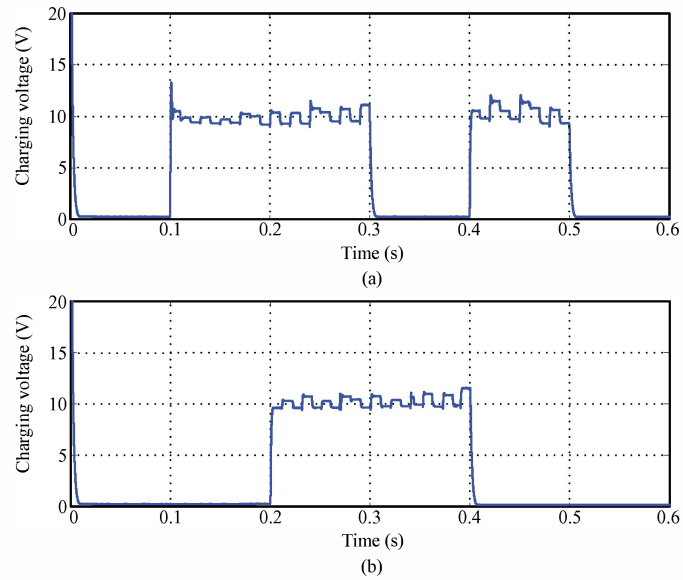


Fig. 5. Simulated charging voltage waveforms: (a) EV-A; (b) EV-B.

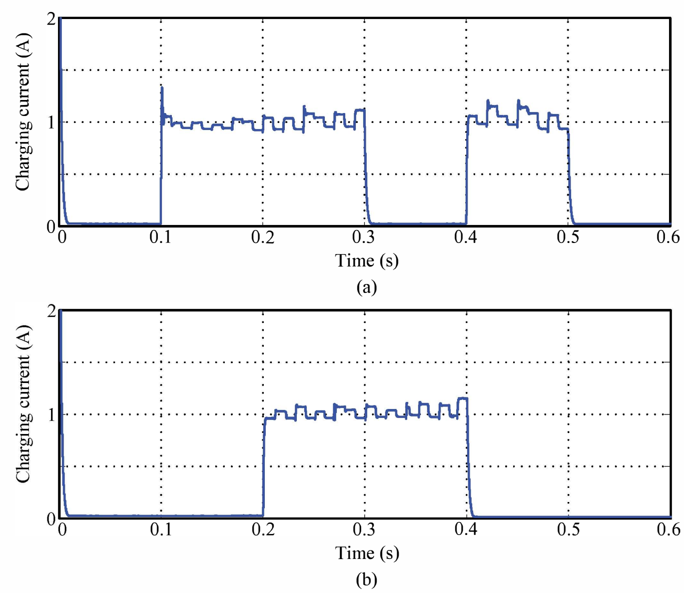


Fig. 6. Simulated charging current waveforms: (a) EV-A; (b) EV-B.

TABLE I

PARAMETERS OF THREE COILS

Item	Value
Primary coil inductance (L_1)	0.09589mH
Primary coil internal resistance (r_1)	0.2215Ω
Primary coil number of turns (N_1)	20
Resonant coil inductance (L_2)	0.09477mH
Resonant coil internal resistance(r_2)	0.07032Ω
Resonant coil number of turns (N_2)	20
Secondary coil inductance (L_3)	0.009372mH
Secondary coil internal resistance(r_3)	0.03565Ω
Secondary coil number of turns (N_3)	10
Mutual inductance (L_{12})	0.005305mH
Mutual inductance (L_{23})	0.007958mH

TABLE II

PARAMETERS OF CAPACITOR ARRAYS

Circuit	Capacitance (nF)					
Power supply unit	C_{11}	C_{12}	C_{13}			
	4.7	10	22			
Resonant unit	C_{21}	C_{22}	C_{23}			
	4.7	10	22			
Receiver unit	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
	1	2.2	4.7	47	100	220

B. Experimental Results

In this paper, the proposed contactless EV charging system is also verified by the downscale experiment. As shown in Fig. 7, the corresponding experimental prototype is established based on the parameters as listed in Table I and Table II. The control of the charging circuit and the proposed energy encryption algorithm is implemented by a standard digital-signal-processing (DSP) microcontroller. The programmable AC power supply (Amplifier Research 75A250A) is utilized as the power source. All waveforms are plotted by using a power analyzer (LeCroy WR6100A) and a wideband current transducer (Tektronix TM502A).

Fig. 8 and Fig. 9 depict the experimental charging voltage and current waveforms for Receiver 1 representing the authorized EV and Receiver 2 representing the unauthorized EV, respectively. It shows that Receiver 1 effectively obtains the charging voltage of 10 V and the charging current of 1 A, while Receiver 2 cannot obtain the wirelessly transferred energy from the power supply. Therefore, the experimental results well agree with the theoretical analysis and the simulated results, which verifies that the proposed contactless charging system can effectively improve the security performance of the wirelessly transferred energy for roadway-powered EVs.

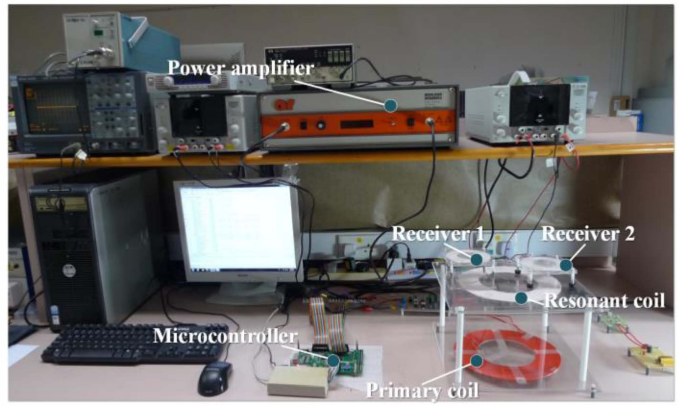
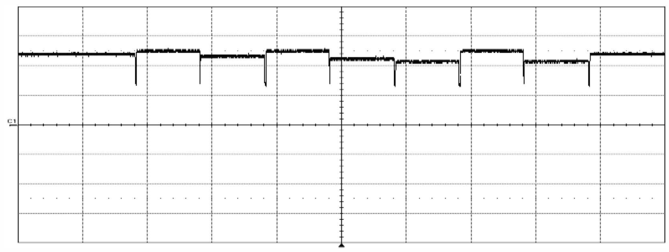
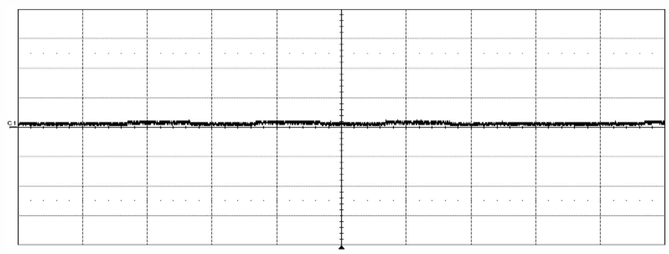


Fig. 7. Prototype of MRC-based contactless EV charging system.

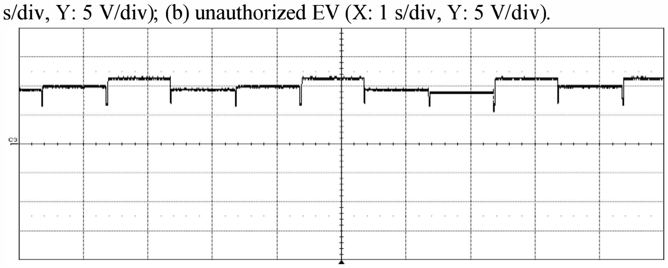


(a)

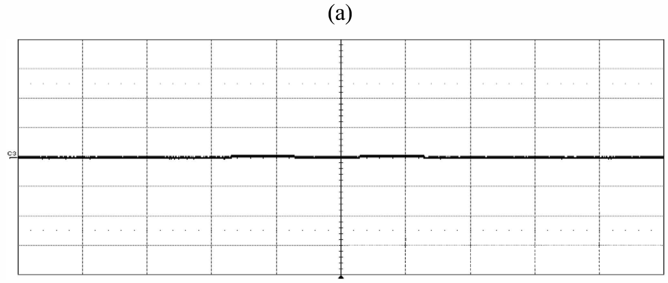


(b)

Fig. 8. Experimental charging voltage waveforms: (a) authorized EV (X: 1 s/div, Y: 5 V/div); (b) unauthorized EV (X: 1 s/div, Y: 5 V/div).



(a)



(b)

Fig. 9. Experimental charging current waveforms: (a) authorized EV (X: 1 s/div, Y: 0.5 A/div).; (b) unauthorized EV (X: 1 s/div, Y: 0.5 A/div).

IV. Conclusion

In this paper, an encrypted roadway contactless EV charging system has been proposed to improve the security performance of the wirelessly transferred energy. The key is to chaotically regulate the switching frequency of the power supply. Then, the energy transmission channel can be turned off for unauthorized EVs. Meanwhile, authorized EVs can effectively receive the transferred energy with the acquired security key. The simulated and experimental results have well agreed with the theoretical analysis and illustrated the effectiveness of the proposed contactless EV charging system.

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