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Energy-Encrypted Wireless Power Transfer for Electric Vehicle Dynamic Charging

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Abstract

This paper proposes and analyses a magnetic coupling-strengthened energy-encrypted wireless power transfer (WPT) system for electric vehicle (EV) dynamic charging. A switched-capacitorless energy-encrypted transmitter and a chaotic 2-D frequency-and-duration encryption (FDE) are introduced to improve wireless energy security. By compacting WPT coils into multiple-layer configurations, both the mutual inductance and magnetic coupling strength are effectively enhanced. The proposed multiple-layer configurations achieve higher transmission efficiency in the proposed coupling-strengthened energy-encrypted WPT system, in which only authorized EVs can successfully implement dynamic charging by decryption. Theoretical analysis and computer simulation are provided to verify the feasibility of the proposed energy-encrypted WPT system.

Keywords: electric vehicle, wireless power transfer, dynamic charging, energy encryption, energy security

1 Introduction

Wireless power transfer (WPT), pioneered by Nicola Tesla more than one hundred years ago [1], has been identified to take the key merits of cordless, convenience and flexibility [2-4] in various industrial applications and interdisciplinary areas, such as electrical vehicle (EV) wireless charging [5-7], wireless motor driving [8-11], wireless heating [12-15] or lighting [16], and consumer or medical electronics [17]. It will be particularly important in both the wireless static charging or dynamic charging [18-20] for hybrid EVs and battery EVs [21, 22]. As one of the most convenient means of transportation, the EVs still can be regarded as carriers of electrical energy [23] for flexible vehicle-to-vehicle, vehicle-to-home and vehicle-to-grid operations [24, 25]. Recently, the epoch-making WPT technology is gradually improving our conventional plug-in charging pattern, thus emerging wireless static charging, dynamic moving-and-charging [26] and even flying-and-charging [27, 28]. Such technologies will effectively extend the traveling range of EVs and alleviate the limitations of current battery techniques [29, 30]. In such ways, various investigations on magnetic sensors have attached new attention of researchers for accurately locating wireless charging objectives and avoiding misalignment [31, 32]. Besides, with the continuous developments in the applications of high-temperature superconductors [33-36] and novel machines for EVs [37-38], high-temperature superconducting WPT systems may show great potentials for EV wireless charging.

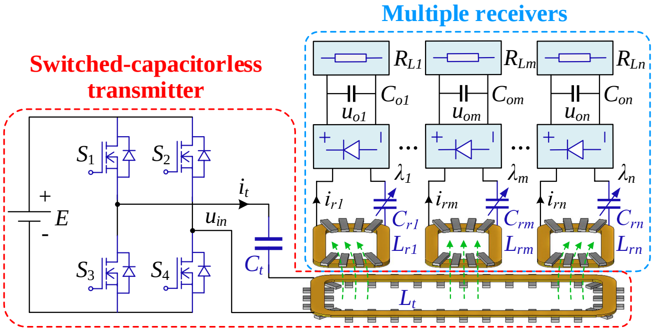
Although the WPT successfully removes the messy charging wires, it inevitably takes the risks of energy stealing or leakage because of such convenient wireless energy-accessing pattern [39]. Therefore, one of the emerging issues in WPT systems, namely wireless energy security, has gradually raised concerns and investigations of consumers, manufacturers and academic researchers. To solve such issues, the concept of wireless energy encryption was firstly proposed in literature [40], which desires to use switched-capacitor arrays to discretely encrypt the wireless energy, thus suffering from finite adjustments and low flexibility. Accordingly, it should be further in-depth investigated to improve encryption performance in a continuous way. As for high-power wireless energy security considerations in the EV wireless charging [41], a continuously variable-frequency switched-capacitorless transmitter, incorporated with a chaotic 2-D frequency-and-duration encryption (FDE) scheme, was presented for wireless energy encryption, thus improving wireless energy security [42]. Also, a variable multi-frequency transmitter can also be adopted to achieve wireless energy encryption. [3]. However, a switched-capacitor array is also used to decrypt the wireless energy in the authorized receivers. Electric springs [43] may be extended to derive an energy-decrypted receiver for wireless energy decryption, but the high-frequency switching operation poses a new challenge in the WPT-based application. Moreover, extra power circuits, such as a switched-capacitor array or an H-bridge inverter, will inevitably increase power losses and reduce system efficiency.

To improve system efficiency while maintaining the superior performance of wireless energy security in EV dynamic charging, this paper proposes and analyses a magnetic coupling-strengthened energy-encrypted WPT system using a switched-capacitorless transmitter for wireless energy encryption. With knowledge of the security keys of chaotic 2-D FDE, only the authorized EVs can successfully decrypt the encrypted wireless power and thus conduct dynamic charging.

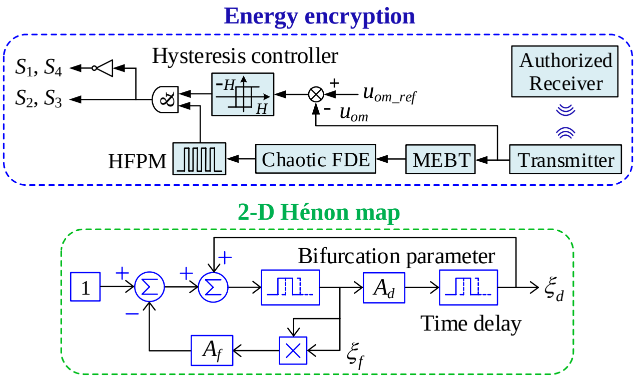
2 Energy-Encrypted Dynamic Charing WPT System

2.1 System Topology

The proposed magnetic coupling-strengthened energy-encrypted WPT system is shown in Figure 1, in which the whole system mainly comprises one switched-capacitorless energy-encrypted transmitter and multiple receivers, namely EVs including authorized and unauthorized ones. A chaotic 2-D FDE algorithm is directly adopted to generate a sequence of more defensive security keys for improving the performance of wireless energy security. Meanwhile, to reduce the switching loss in pulse width modulation [44, 45], hysteresis control, incorporated with high-frequency pulse modulation (HFPM) [46], is used to control the output power at variable operating frequencies. Generally, the transmitter coil is mounted below the charging roads or parking lots, while the receiver coil is installed on the bottom of EVs. Aiming to strengthen magnetic coupling and compact wireless charging system, the multiple-layer concentrated coil configuration is firstly introduced to replace its conventional single-layer counterparts. As a result, the proposed coupling-strengthened energy-encrypted WPT system using multiple-layer configurations can achieve higher transmission efficiency while maintaining the superior performance of wireless energy security.



(a)



(b)

Figure1: Proposed magnetic coupling-strengthened FDE-WPT system using switched-capacitorless transmitter. (a) Topology. (b) Control and chaotic 2-D FDE.

2.2 Operating Principle

According to the security keys of chaotic 2-D FDE sequences, the switched-capacitorless transmitter will encrypt the wireless energy into encrypted energy packages. With knowledge of the security keys secretly delivered from the energy-encrypted transmitter, only specific EVs are authorized to decrypt and pick up the wireless energy-encrypted packages. As depicted in Figure 1(a), R_t, L_t, C_t, i_t, R_{rk}, L_{rk}, C_{rk} and i_{rk} ($k \in Z^+$) with subscripts t and r denote the coil internal resistances, resonant coil inductances, matched capacitances and currents in the transmitter and receiver circuits in the kth energy-encrypted WPT channel, respectively. Besides, L_{trk} and $L_{rk_1k_2}$ ($k_1, k_2 \in [1, n]$) denote the mutual inductance between the transmitter coil and the kth receiver coil and that between the k_1th and k_2th receiver coils, respectively. Besides, λ_k obeys a random distribution, which represents the number of receivers in the kth energy-encrypted WPT channel. To commence with theoretical analysis, some assumptions are made: (i) $L_{rk}=L_r$, $L_{trk}=L_{tr}$, $R_{rk}=R_r$, and $R_{Lk}=R_L$. (ii) R_{Lk_eq} is the equivalent resistance of load resistance R_{Lk}, and $R_{Lk\_eq}=8R_{Lk}/\pi^2$. (iii) $L_{trk} >> L_{rk_1k_2}$, and $L_{rk_1k_2}$ can be regarded as zero.

When the mth group of EVs is authorized, both the transmitter and the mth group of authorized EVs operates at the energy-encrypted resonant frequency f_m. In such a way, the general equation can be derived as:

$$\begin{bmatrix} Z_t & Z_{tr1}\lambda_1 & \cdots & Z_{trm}\lambda_m & \cdots & Z_{trn}\lambda_n \\ Z_{tr1} & Z_{r1} & \cdots & Z_{r1m}\lambda_m & \cdots & Z_{r1n}\lambda_n \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{trm} & Z_{r1m}\lambda_1 & \cdots & Z_{rm} & \cdots & Z_{rmn}\lambda_n \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{trn} & Z_{r1n}\lambda_1 & \cdots & Z_{rmn}\lambda_m & \cdots & Z_{rn} \end{bmatrix} \begin{bmatrix} i_t \\ i_{r1} \\ \vdots \\ i_{rm} \\ \vdots \\ i_{rn} \end{bmatrix} = \begin{bmatrix} u_{in} \\ 0 \\ \vdots \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{1}$$

where $Z_{trk} = j\omega_m L_{trk}$, $Z_{rk_1k_2} = j\omega_m L_{rk_1k_2}$ and ω_m is the angular frequency corresponding to f_m. Besides, Z_t, Z_{rk} and Z_{rm} denote the impedances of the energy-encrypted transmitter, the kth and mth secondary circuits operating at f_m, respectively. They can be calculated as:

$$\begin{cases} Z_t = R_t + j\omega_m L_t + \dfrac{1}{j\omega_m C_t} \\ Z_{rk} = R_{Lk} + R_{rk} + j\omega_m L_{rk} + \dfrac{1}{j\omega_m C_{rk}} \\ Z_{rm} = R_{Lm\_eq} + R_{rm} \end{cases} \tag{2}$$

Its corresponding transmission efficiency η_k in the kth WPT channel can be calculated as:

$$\eta_k = \frac{P_{\text{out}k}}{P_{\text{in}}} = \frac{\lambda_k R_{Lk\_\text{eq}} \left(\omega_m L_{trk}\right)^2}{\left|Z_{rk}\right|^2 \left(\text{Re}\left(\sum_{k=1}^{n} \lambda_k Z_{\text{ref}k} \right) + R_t \right)} \tag{3}$$

No matter the transmitter operates at resonance or not, the corresponding mth transmission efficiency can be derived as:

$$\eta_m = \frac{R_{L\_\text{eq}}}{R + \sum_{k=1,\, k\neq m}^{n} \frac{\lambda_k R^3}{\lambda_m \left[R^2 + \left(\omega_m L_s - 1/\omega_m C_{rk}\right)^2 \right]} + \frac{R_t R^2}{\lambda_m \left(\omega_m L_{tr}\right)^2}} \tag{4}$$

where $R = R_r + R_{L\_\text{eq}}$.

Accordingly, both transmission efficiencies η_k and η_m are impervious to the transmitter resonance parameters L_t and C_t. Although the internal resistance R_t of the transmitter coil leads to extra power loss, the proposed system takes the advantage of magnetic coupling enhancement and lower power loss in the transmitter over the conventional energy-encrypted WPT system using switched-capacitor arrays [40].

By adopting various compensated capacitances in the transmitter, the ratio of f/Z_{in} versus the encrypted frequency band is plotted in Figure 2, where Z_{in} is the input impedance in the output side of the inverter. Approximately, a constant ratio of f/Z_{in} can achieve constant output wireless power within the selected encrypted frequency band. Thus, the harvested wireless power can be optimized with fewer fluctuations by designing an appropriate transmitter compensated capacitance (4.45 nF) as shown in Figure 2.

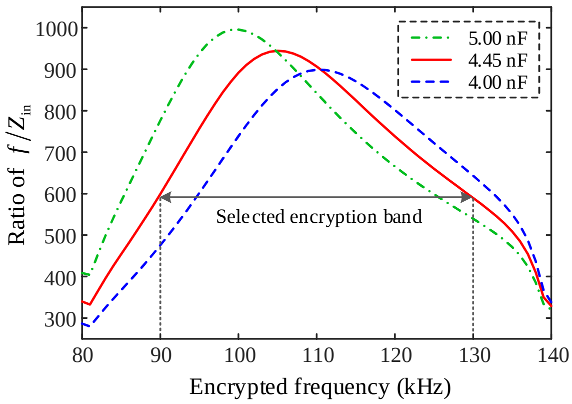


Figure 2: Ratio of f/Z_{in} versus encrypted frequency band with various compensated capacitances in transmitter.

2.3 Magnetic Coupling Enhancement

Assuming the WPT coils are circuar, the mutual inductance between two circular filaments can be calculated as [47]:

$$L_M = \mu_0 \pi r_t r_r \int_0^\infty J_1\left(kr_t\right) \cdot J_1\left(kr_r\right) e^{-kD} dk \tag{5}$$

where J_1 is a Bessel function of the first kind, μ_0 is the air permeability, and the equivalent radii of transmitter and receiver filament coils $r_x = \left(r_{o-xk} + r_{i-xk}\right)/2 \left(x \in \{t, r\}\right)$, respectively. The remaining dimensions are shown in Figure 3. By integrating the filament formula (14), the mutual inductance between the transmitter and receiver coils can be derived as:

$$L_{Mtr} = \frac{1}{d^4} \int_{r_{i-tk_t}}^{r_{o-tk_t}} \int_{r_{i-rk_r}}^{r_{o-rk_r}} \int_{-k_t d/2}^{k_t d/2} \int_{-k_r d/2}^{k_r d/2} L_M \, dr_t dr_r d\tau_t d\tau_r \tag{6}$$

where k_t and k_r are the layer numbers of transmitter and receiver coils, respectively.

Assuming the multiple-layer configurations have the same turns with its single-layer counterparts, although the acreage for surface integral keeps constant, the multiple-layer concentrated configurations can enlarge the radius r_x and thus the mutual inductance L_M. Although the adopted WPT coils for EV dynamic charging may be not ideal circular, they have the same mechanism for mutual inductance enhancement because the adopted WPT coils can be approximately equivalent to their circular counterparts. Consequently, the total mutual inductance L_{Mtr} as well as magnetic coupling strength are effectively enhanced.

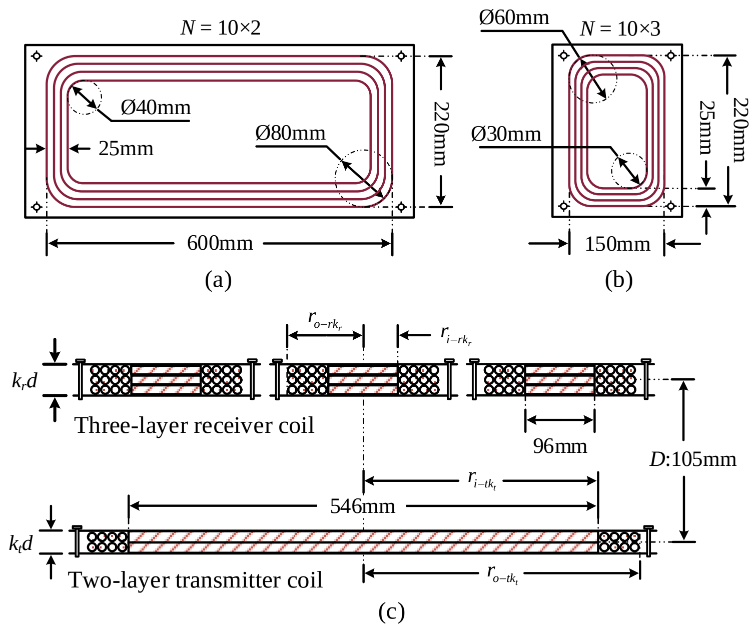


Figure 3: Geometries of transmitter and receiver coils. (a) Transmitter coil. (b) Receiver coils. (c) Displacement among coils.

3 Chaotic 2-D Frequency-and-Duration Encryption

The key of energy encryption mainly relies on the frequency sensitivity in the conventional magnetic resonant coupling WPT systems. The proposed magnetic coupling-strengthened energy-encrypted WPT scheme is depicted in Figure 4, where the control unit generates more defensive chaotic 2-D FDE sequences, namely the security keys. Based on the wireless data interaction between the energy-encrypted transmitter and energy-decrypted EVs, the control unit will conduct the maximum efficiency band tracking (MEBT) to suppress the wireless energy leakage. Practically, the operating frequencies of the unauthorized EVs always dynamically and randomly change, which will unexpectedly result in an increasing probability of wireless energy stealing or leakage. Thus, the MEBT will dynamically optimize the energy-encrypted frequency band for maximizing transmission efficiency. According to the optimized security keys, the switched-capacitorless transmitter will encrypt the wireless energy into encoded energy packages. This energy encryption is realized by proactively attuning both the switching frequency and its duration to the FDE security keys. After certificating the authorization of specific EVs, the FDE security keys will be secretly delivered to the authorized EVs. With knowledge of the FDE security keys, the authorized EVs will decrypt the encoded energy packages by adjusting their switched-capacitor arrays. Thus, they can effectively harvest wireless energy from the proposed magnetic coupling-strengthened energy-encrypted WPT system. Due to the lack of security keys, the unauthorized EVs can pick up only an insignificant level of encrypted wireless energy.

In Figure 4(b), a chaotic 2-D FDE algorithm is directly adopted to dynamically generate the encrypted frequency and its active duration sequences – the security keys. It plays an important role in ensuring wireless energy security. The Hénon map is used to generate a 2-D discrete-time chaotic series [48, 49] as given by:

$$\begin{cases} \xi_{f\_i+1} = \xi_{d\_i} + 1 - A_f \xi_{f\_i}^2 \\ \xi_{d\_i+1} = A_d \xi_{f\_i} \end{cases}, \; A_f \in [1.0, 1.5], \; A_d = 0.3 \quad (7)$$

where ξ_{f_i} and ξ_{d_i} are the chaotic sequences of the energy-encrypted frequency and its duration, respectively, and A_f and A_d are the corresponding bifurcation parameters. To produce the desired random-like but bounded security keys (ξ_f, ξ_d) for the proposed energy-encryption scheme, A_f =1.4 is selected [49]. Hence, the chaotic security keys γ_i and β_i can be expressed as:

$$\begin{cases} \gamma_i = a_\gamma + b_\gamma \xi_{f\_i}, \ 0 < 1.5\, b_\gamma < a_\gamma \\ \beta_i = a_\beta + b_\beta \xi_{d\_i}, \ \ 0 < 0.4\, b_\beta < a_\beta \end{cases} \tag{8}$$

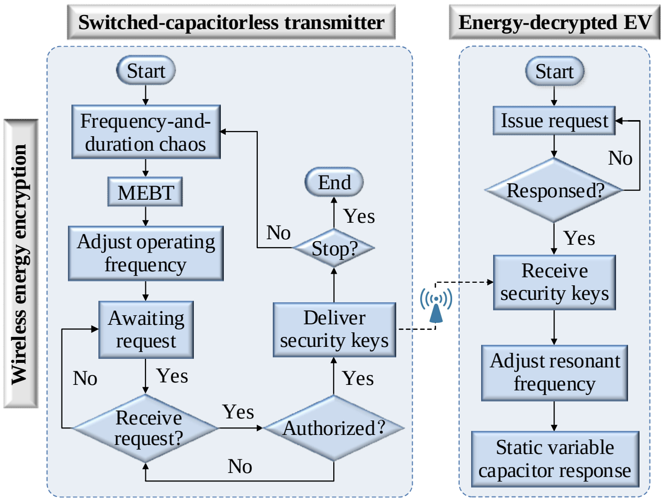


Figure 4: Flowchart of proposed chaotic 2-D FDE.

Accordingly, the encrypted angular frequency ω_m and its duration D_m can be respectively expressed as:

$$\begin{cases} \omega_m = \gamma_i \omega_0 \\ D_{m\_q} = \beta_i D_0, \ q \in Z^+ \end{cases} \tag{9}$$

Thus, both the encrypted operating angular frequency and its duration can be chaotically varied in the proposed magnetic coupling-strengthened energy-encrypted WPT system. Generally, ω_0 and D_0 can be arbitrarily designed based on the power level and transmission distance. Instead of simultaneously regulating switched-capacitor arrays in both the transmitter and the authorized EVs [40], the switched-capacitorless transmitter can self-adaptively attune the switching frequency to synchronize the FDE security keys. Meanwhile, with knowledge of the security keys, the authorized EVs will synchronize their operating frequency to the FDE security keys for wireless energy decryption by adjusting the switched-capacitor array. Accordingly, the matched capacitor in the authorized EVs will be adjusted as:

$$C_{rb}\left(\sum_{q=1}^{q=i} \left(\beta_i D_0 \right) \right) = \frac{1}{r_i^2} \frac{1}{\omega_0^2 L_{rb}} \tag{10}$$

Consequently, the encoded energy package can only be decrypted by those authorized EVs with knowledge of security keys.

4 Verifications and Discussions

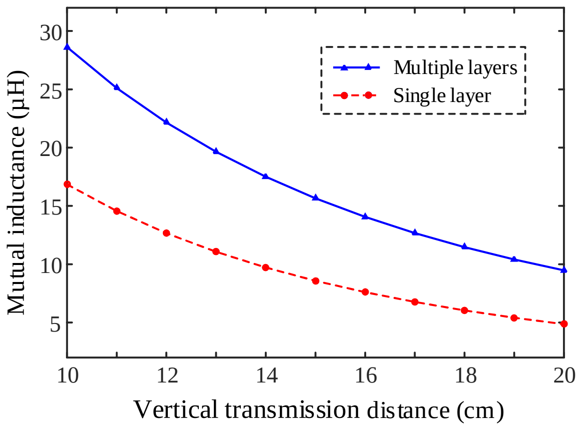
To verify the proposed magnetic coupling-strengthened energy-encrypted WPT system, finite element analysis (FEA) and system simulation are performed. The key design specifications and parameters are listed in Table I. Detailed geometries with dimensions of the transmitter and receiver coils are depicted in Figure 3, where the transmitter and receiver coils respectively adopt a two-layer and three-layer configurations. The transmission distance is 105 mm and each receiver coil can be separately authorized to decrypt and pick up the encrypted wireless power.

By using FEA with a 10-A AC current source, the mutual inductance enlargement and transmission efficiency improvement, as well as magnetic coupling enhancement, are simulated and well confirmed in Figure 5.

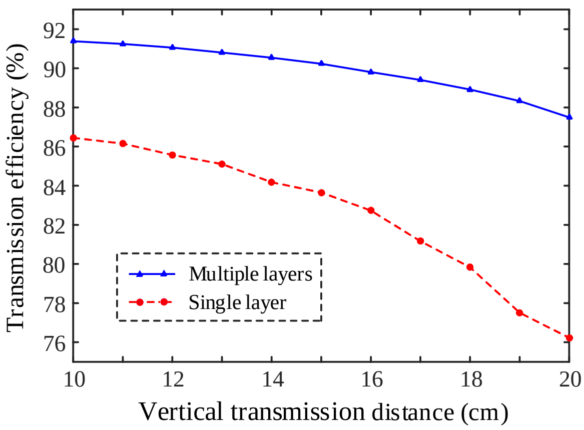
When the central receiver is authorized, Figure. 5(a) and (b) demonstrates that the enhanced mutual inductance and the improved transmission efficiency by adopting the proposed multiple-layer configurations in the WPT coils. Notedly, the transmission distance is the vertical distance between the energy-encrypted transmitter and the bottom of EVs. Generally, it ranges from 10 cm to 20 cm. Along the vertical plane, the contour plots of magnetic flux densities are plotted in Figure. 5(c) and (d), where the magnetic flux densities around the authorized EV coil are far higher than those around the unauthorized ones by applying the proposed 2-D FDE scheme. Also, the magnetic flux densities around the authorized EV coil is effectively improved by adopting the proposed multiple-layer configurations as compared with those using the single-layer configurations. Along the middle parallel plane, the 3-D magnetic flux densities are plotted in Figure 5(e) and (f), where the 3-D magnetic flux densities under the authorized EV coil can reach up to 2.906 mT and 3.858 mT by adopting the single-layer and proposed multiple-layer configurations, respectively. Thus, the magnetic coupling enhancement is well confirmed by adopting the proposed multiple-layer configurations.

Table 1: Design specifications and parameters

Items	**Value**
DC power source (E)	500 V
FEA AC current source (I_{in})	10 A
Transmitter compensated capacitance (C_t)	4.45 nF
Transmitter coil inductance (L_t)	493.55 µH
Transmitter coil turns (n_t)	20 (2 layers)
Transmitter coil internal resistance (R_t)	0.4 Ω
Receiver compensated capacitances (C_{rk})	3.48~11.56 nF
Receiver coil inductances (L_{r1}, L_{rm}, L_{rn})	315.24, 315.12, 315.22 µH
Receiver coil turns (n_{rk})	30 (3 layers)
Receiver coil internal resistance (R_{rk})	0.3 Ω
Mutual inductances (L_{tr1}, L_{trm}, L_{trn})	28.617, 33.024, 28.617 µH
Energy-encrypted frequency (f_k)	80~140 kHz
Output filter capacitance (C_o)	4700 µF



(a)



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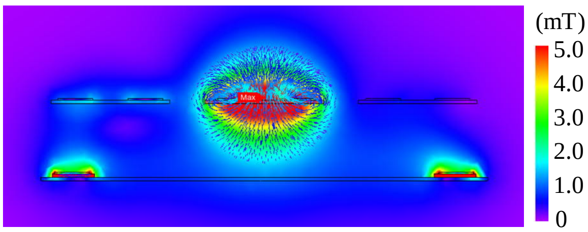
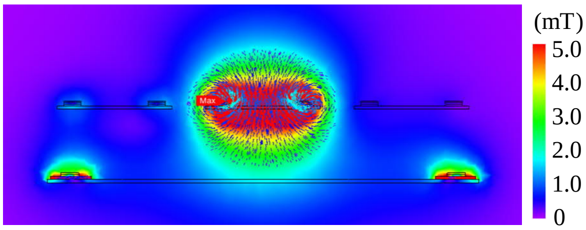
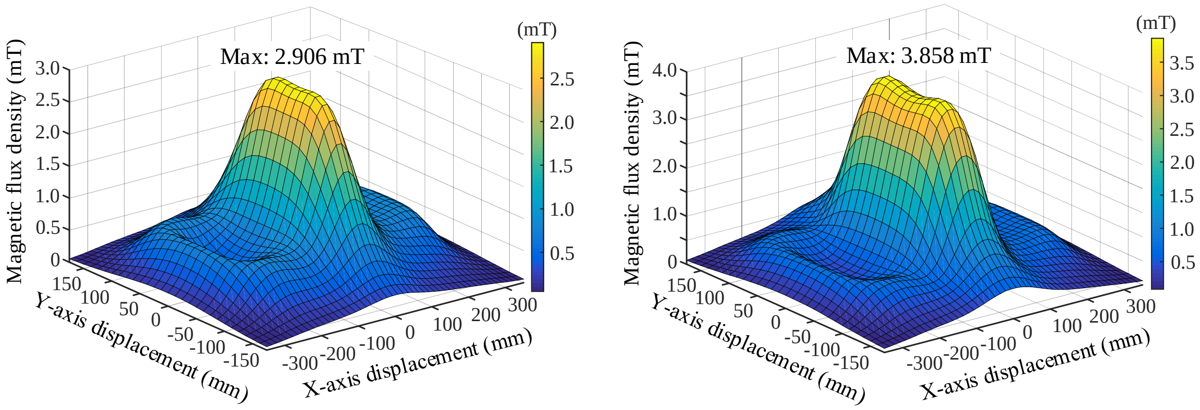


(c)



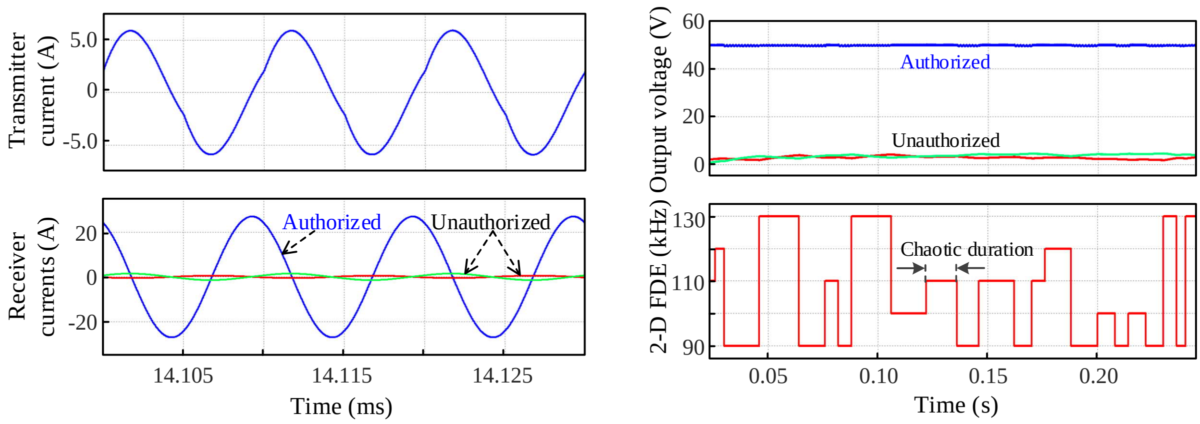
(d)



(e) (f)

Figure 5: Electrical characteristics and magnetic field distributions using single-layer and multiple-layer WPT coils. (a) Mutual inductances. (b) Transmission efficiencies. (c) Flux densities along vertical plane (single layer). (d) Flux densities along vertical plane (multiple layers). (e) Flux densities along middle parallel plane (single layer). (f) Flux densities along middle parallel plane (multiple layers).

Furthermore, the energy security performances of the proposed chaotic 2-D FDE-WPT system are demonstrated in Figure 6. Figure 6(a) shows that the authorized EV current can reach up to 19.13 A, much larger than the unauthorized EV currents (0.38 A and 1.02 A). Figure 6(b) shows that both the operating frequency and its active duration are simultaneously encrypted in a 2-D scale to improve the energy security performance. With knowledge of security keys, the authorized EV can always successfully decrypt and pick up the encrypted wireless power, thus generating an average output voltage of 49.93 V, while the unauthorized EVs fail to decrypt and harvest nearly no power from the proposed energy-encrypted WPT system, hence only generating insignificant values of 2.85 V and 3.67V. Correspondingly, the average wireless power harvested by the authorized EV is 498.6 W, far greater than those (1.62 W and 2.69 W) harvested by the unauthorized ones. Only 0.857% wireless power is stolen by the unauthorized EVs among all the EVs. The authorized charging power can be further increased by enlarging output voltage reference in the closed-loop control, while the unauthorized charging can always be successfully blocked. Therefore, the proposed magnetic coupling-strengthened energy-encrypted WPT scheme effectively guarantee the energy security for EV dynamic charging while improving transmission efficiency.



(a) (b)

Figure 6: System performances of proposed magnetic coupling-strengthened 2-D FDE-WPT. (a) Transmitter and three EV currents. (b) Security performance.

5 Conclusions

A magnetic coupling-strengthened energy-encrypted WPT system has been proposed and analysed for EV dynamic charging. In the proposed energy-encrypted WPT system, a switched-capacitorless transmitter, incorporated with chaotic 2-D FDE security keys, is introduced to improving the wireless energy security performance. The magnetic coupling enhancement is effectively realized by compacting single-layer configurations to be multiple-layer ones in both transmitter and receiver coils. As a result, the proposed magnetic coupling-strengthened energy-encrypted WPT using multiple-layer configurations achieves higher transmission efficiency. Also, the proposed WPT system can guarantee that only authorized EVs successfully decrypt the encrypted wireless energy for dynamic charging, thus suppressing wireless energy stealing or leakage. The feasibility of the proposed coupling-strengthened energy-encrypted WPT system is verified by both theoretical analysis and computer simulation.

Acknowledgments

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