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Idaho National Laboratory

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Quasi-Dynamic Electromagnetic Field Safety Analysis and Mitigation for High-Power Dynamic Wireless Charging of Electric Vehicles

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Abstract— **Dynamic wireless charging of electric vehicles (EV) is an emerging charging technology to enable non-contact wireless charging while the vehicle is moving. Compared to stationary wireless charging, in-motion wireless charging involves dynamic processes in which an EV is passing over the charging pads (transmitters). This in-motion process makes the dynamic electromagnetic (EM) environment more complicated, and EM safety needs to be ensured under all circumstances. This is due to the fact that the entire vehicle body may be exposed to magnetic fields while the vehicle moves over the energized transmitter. This paper investigates several typical charging scenarios when EVs approach, pass over, and move away from the charging pads. Quasi-dynamic models, which are preliminarily verified by coils' inductance measurements, are developed to analyze the dynamic process. Based on the quasi-dynamic analysis, shielding solutions are also studied to ensure EM safety for the dynamic wireless charging processes.**

Keywords— ***wireless power transfer, inductive power transfer, dynamic wireless power transfer, electric vehicle, electric vehicle charging, electromagnetic field, shielding.***

I. Introduction

Dynamic wireless power transfer (dWPT) is a newly developed, convenient, and flexible wireless charging technology [1]-[3]. In contrast to stationary wireless charging, in-motion charging is the key feature that enables longer range between stops to charge at a stationary charger. Besides the in-motion feature, dWPT can implement charging without stop or wait, and thus reduces the driving range limitations created by limited battery capacity on an EV, especially for EVs operating in a routine or loop routes.

To increase the energy transfer for during a short period of time, high-power charging is typically preferred. As the charging power goes higher, electromagnetic (EM) safety becomes a concern [4], and the EM emission for dWPT will become more complicated since the vehicle moves over the energized transmitters. Some passive shielding solutions have been developed for stationary 200 kW wireless charging of light-duty electric vehicles (LDEVs) [5], [6]. However, the EM safety for an in-motion charging process needs further study.

Most of the publications in the field of dWPT mainly focus on dWPT control or interoperability studies [7]-[11]. In terms of ensuring EM safety, reference [12] presents a control strategy to mitigate the stray EM fields. Several ferrite shielding designs with different geometries are proposed to mitigate leakage flux for roadway-powered EV applications in [13]. A multi-objective optimization strategy to improve the magnetic coupling and reduce EM-field emission is discussed in [14]. These methodologies are effective solutions to mitigate EM emissions; however, application focuses are neither static wireless power transfer (WPT) nor dWPT system but heavy-duty vehicles. To achieve 200 kW dWPT integrated with LDEVs, advanced shielding solutions to ensure EM safety are required.

This paper investigates EM safety of dWPT considering different dynamic scenarios that involve an EV's approaching, passing over (both for aligned and misaligned cases), between charging pads, and moving away from the charging pads. The safety limitation for dWPT are discussed. Quasi-dynamic models, which are preliminarily verified by static couplers' mutual-inductance measurements, are developed to analyze different positioning scenarios. Based on the simulation analysis, a feasible shielding solution that ensures EM safety for the whole dynamic process is also provided. This paper focuses on the magnetic field emissions. The electric-field aspect, which is typically not a critical concern for WPT based on studies presented in [15], is not discussed here and will be studied in the future.

II. DWPT Process and Scenarios

Figure 1 presents a typical dWPT application scenario. In the specially planned electrified lane, high-power wireless charging pads are installed in the roadway. When LDEVs pass over, ground-side wireless pads are energized sequentially to charge the in-motion LDEVs. At highway driving speeds, i.e., 70 MPH, vehicles spend only tens of milliseconds over the transmitters. Therefore, it is difficult to energize the transmitter only when the receiver is

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over the transmitter. Instead, transmitters are usually energized when the vehicle is approaching with the aid of a vehicle detection system and the transmitters are kept on until the vehicle clears a transmitter or a group of multiple transmitters. Therefore, the vehicle during the charging process is typically exposed to EM-fields which leads to safety concerns.

EM safety for dWPT was discussed in previous publications based on a simple static assumption [4], [16], [17]. However, the in-motion dWPT process should also be taken into account. In the driving direction, LDEV can be aligned with one ground-side coil, as shown in Fig. 2 (a), or positioned between two ground-side coils, as shown in Fig. 2 (b). The condition shown in Fig. 2 (b) occurs when the distance between two transmitters is less than the length of the LDEV. In the transverse direction, LDEV can run exactly along the charging pads' line, or with lateral misalignments, as shown in Fig. 2 (c). To ensure EM safety under the worst case, those scenarios need to be investigated.

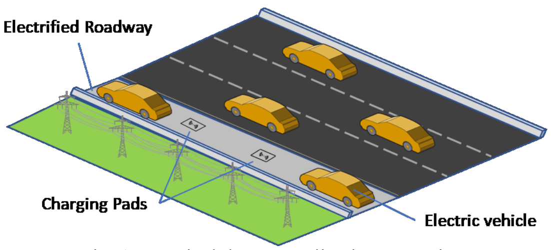
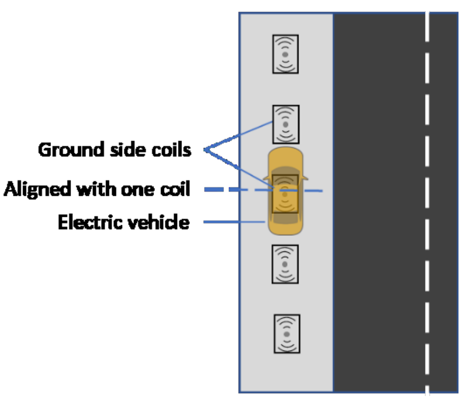
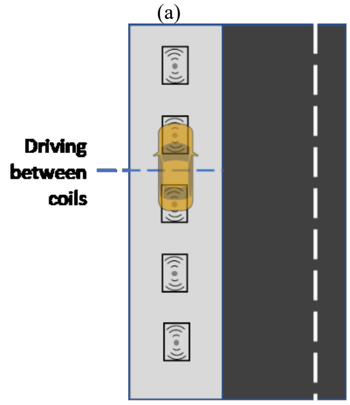


Fig. 1. Typical dWPT application scenario.



(a)



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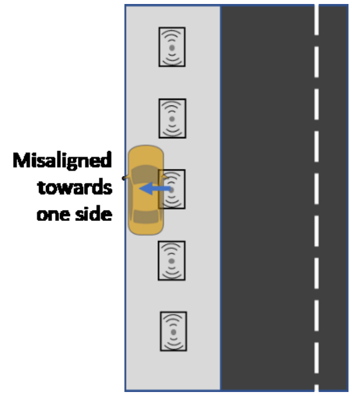
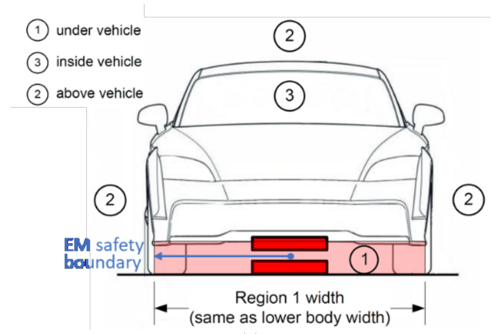


(c)

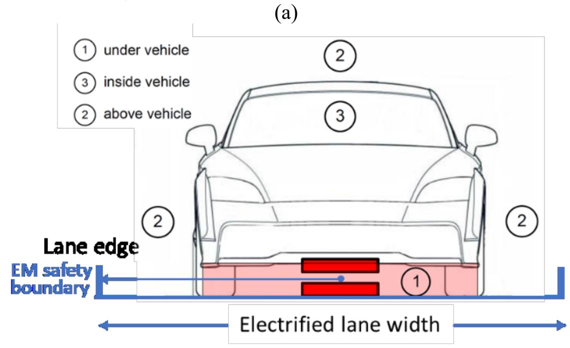
Fig. 2. Different scenarios when (a) vehicle is aligned with only one ground-side coil, (b) vehicle is transitioning from one ground-side coil to the other, and (c) vehicle is laterally misaligned.

III. EM Safety Limit Discussion

Society of Automotive Engineers (SAE) Standard J2954 defines a maximum allowed magnetic field of 27 µT at 0.8 m from the center of the vehicle-side coil for LDEV stationary WPT. For those with implanted medical devices, the safety limit is defined as 15 µT [18]. The 27-µT or 15 µT criteria is adopted from the ICNIRP 2010 guideline [19], and the 0.8-m criteria, as shown in the blue arrow of Fig. 3 (a) [18], is derived from the width of an LDEV that is typically 1.6 m .



(a)



(b)

Fig. 3. (a) EM safety criteria for stationary WPT according to SAE standard J2954 [18] and (b) the proposed EM safety distance criteria for dWPT.

No standard exists yet for dWPT. Considering the real-world in-motion charging scenario, the EM safety-distance criteria for dWPT is likely a further distance than stationary WPT's criteria of 0.8 m. The potential for injury or death is much higher when being struck by a vehicle in motion than the safety risk of exposure to strong EM. Considering the preference to install dWPT along a freeway, where pedestrians or pedestrian crossing are prohibited within the electrified lane, the lane edge of the roadway is a good EM safety boundary for dWPT.

The distance criteria for EM safety of dWPT is still an open question. The U.S. typical freeway lane width is 3.7 m while the narrowest lane in Japan is only 2.75 m. In this paper, 1.35 m, less than half of the narrowest Japanese lane width, is proposed as a preliminary distance criterion between lane edge and charging pads for dWPT EM safety evaluation, as shown in Fig. 3 (b). Note that this 1.35 m distance criterion is for EM safety evaluation external (Region 1 and 2 in Fig. 3 (b)) to the vehicle only while the internal (Region 3 in Fig. 3 (b)) driver's safety criteria should still comply with safety limits defined in SAE Standard J2954.

IV. Circuit Model and EM Shield for DWPT

A. *Circuit Schematic for DWPT*

EM safety is the focus in this paper, rather than wireless-charging circuit design; therefore, a generic WPT resonant circuit is presented here as an example to conduct analysis for dWPT, as shown in Fig. 4. This circuit is derived from electric to magnetic to electric energy-conversion mechanism, and it is applicable to all power-electronics charging topologies regardless of the resonant tuning network (series-series, LCC-series, or LCC-LCC) [20], [21]. In this circuit, v_{g1}, i_{g1}, C_{g1}, R_{g1}, L_{g1}, and v_{gn}, i_{gn}, C_{gn}, R_{gn}, L_{gn} represent the ground-side voltages, currents, compensation capacitors, coil resistances, and coil self-inductances of the 1^{st} or n^{th} ground-side charging circuit, respectively; v_v, i_v, C_v, R_v, and L_v represent the vehicle-side voltage, current, compensation capacitor, coil resistance, and coil self-inductance, respectively. M_1 or M_n is the mutual inductance between the n^{th} ground-side coil and vehicle-side coil, and Z_{Lac} is the AC-side equivalent load impedance. The AC side equivalent resistor Z_{Lac} in Fig. 4 can be obtained from battery's equivalent DC load impedance Z_0 as below [22], [23],

(1)

Accordingly, v_v in Fig. 4 can be given as:

(2)

where V_0 is the DC side battery voltage.

The wireless charging circuit equations can be given by:

(3)

(4)

Assuming that R_v is negligible compared to Z_{Lac}, the output power on the vehicle side can be written as:

(5)

where I_{gn}, I_v are the RMS values of the ground- and vehicle-side currents, respectively; and is the power factor on the vehicle side.

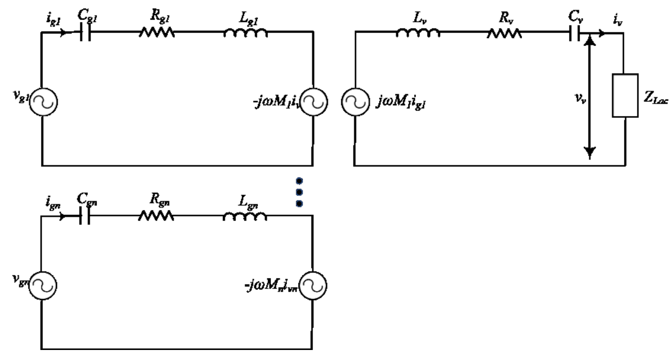


Fig. 4. Generic charging schematic for dWPT.

B. *Quasi-Dynamic Simulaton Model and EM Shield*

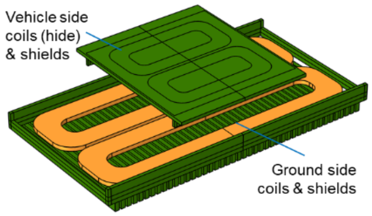
Based on circuit schematic of Fig. 4 and circuit equations (3-5), finite-element models are developed for EM-field analysis. Main circuit parameters used for simulations in this paper are listed in Table I, and other detailed circuit and coil dimensions are presented in [21]. To investigate EM emissions during the whole in-motion charging process, different scenarios, as discussed in Section 2, are modeled and studied by using finite-element analysis.

Table I
Main Circuit Parameters of the Proposed 200 kW DWPT [21]

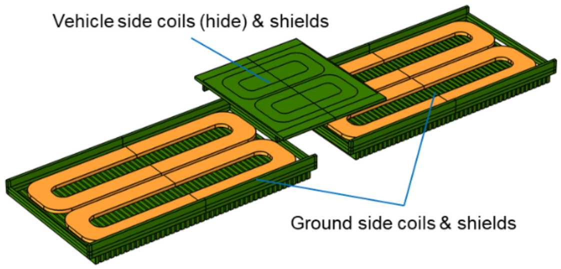
Parameters	Value [unit]
resonant frequency	85 [kHz]
output power	200 [kW]
output voltage	400 [VDC]
vehicle-side resonant topology	LC
ground-side resonant topology	LCC
vehicle-side coil type	DD
ground-side coil type	DD
shielding	passive ferrite shield

Theoretically, the moving speed of a vehicle passing over a charging pad needs to be considered for complete transient analysis, which induces EM forces due to Lenz's Law. But the focus of this study is the EM-field emission around the electrified lane, instead of induced EM forces. Therefore, to simplify the analysis, vehicle speed interacting with the EM field is not considered in the modeling, but transient voltages, currents, and EM fields, as well as induced eddy-current effects are all taken into account. Since this is not a full transient model, it is called a quasi-dynamic EM model in this paper. To analyze the whole passing process of DWPT, different scenarios, as mentioned in Fig. 2 of Section II, are analyzed. For each scenario, alignment and misalignment cases are also studied.

Following the previous EM shield design for a 200 kW stationary WPT, published in [5], an improvement of shaped shield design to enable in-motion DWPT is also developed, as shown in Fig. 5, with coil dimensions still referred to [21]. Figure 5 (a) presents the model when EV is aligned with one ground-side charging pad as mentioned in the scenario of Fig. 2 (a) while the Fig. 5 (b) presents the simulation model when EV is positioned between two ground-side charging pads as shown in the scenario of Fig. 2 (b).



(a)



(b)

Fig. 5. EM-safety simulation model and proposed shielding design for DWPT when (a) the vehicle is aligned with one ground-side coil and (b) vehicle is positioned between two ground-side coils.

In addition to ferrite backplate-based shielding that is recommended in SAE J2954 [18] as a default shielding solution for stationary WPT, ferrite teeth are further added in this design on the edges of both ground and vehicle-side backing ferrites to centralize fields and reduce emission, similar to the previous EM-shield design work for a 200 kW stationary WPT published in [5]. Since the ground-side coils are much wider than the vehicle-side coil due to EV's limited space for coil installation, back ferrites are extended on the vehicle-side shielding to ensure EM safety in the case of misalignment. Due to the anisotropy field distribution created by DD coils, back ferrites extension is only in the transverse direction for size and weight consideration. Since many ferrites are needed for the ground-side charging pads along the electrified lane, ferrite sticks instead of tiles, as shown in Figure 5, are utilized in the proposed dWPT system for procurement and assembling consideration. Note that symmetric boundary conditions in simulation models of Fig. 5 are also applied to mimic multiple ground-side coils in each case.

V. Model Verification and EM Safety Results

A. *Static Model Verification with Mutual-Inductance Measurements*

To verify the finite-element model presented in Figure 5, mutual-inductance is calculated by using the model and then compared with measurements. Normally, it is not difficult to calculate mutual inductance based on equations (3) and (4) with short-circuit method, where self-inductance in those equations can be calculated as below,

(6)

where E is the total spatial EM-field energy integration when only one (e.g., the ground-side coil) is excited with all other coils are open-circuited.

But potential inaccuracy might occur by using this traditional circuit computing when mutual inductance is small. The fabricated coils in the proposed dWPT have a small mutual inductance M of 1.45 μH, compared to the self-inductance, L_v of 21.85 μH. To improve the mutual-inductance calculation's accuracy, the electromagnetic energy method is used here instead of the circuit method so that the mutual inductance can be calculated without depending on the self-inductance calculation.

Assuming the ground-side and vehicle-side coils are in a corresponding coupling direction, based on transformer equivalent circuit theory, the input equivalent inductance in this case can be written as:

(7)

Assuming the equivalent current flowing in both ground-side and vehicle-side coils are I, Equation (7) can be rewritten as,

(8)

Similarly, the input equivalent inductance when the ground-side and vehicle-side coils are in opposite coupling direction can be written as:

(9)

Equation (8) subtracting Equation (9) gives the following expression,

(10)

Noting that for this proposed dWPT system, , so the equivalent current I in Equation (10) is for mutual-inductance calculation purpose only. Moreover, the identical current I in the circuit will lead to different currents flowing in both ground-side and vehicle-side coils due to the different wiring turns accordingly.

With Equations (10) and (6), the mutual inductance and self-inductance are calculated. The vehicle-side coils' self-inductance is obtained as 21.3 μH in simulation, which agrees well with the 21.85 μH inductance in measurement. Since a simplified multiturn coil model is utilized here as an example without modeling mechanical details and leads on the ground-side coil, as shown in Figure 5, the ground-side coil's self-inductance is calculated as 5.63 μH in simulation while the actual measured inductance, including leads and connecting wiring inductance, is 8.24 μH. Practically, it is normal to have 1- 2 μH wiring inductance variation because of wiring route and fabrication details, which lead to the differences between simulation and measurement especially when inductance is small. But based on Equation (10), mutual inductance between ground-side and vehicle-side coils can still be calculated without depending on self-inductances calculation. The calculated mutual inductance referring to Equation (10) is 1.47 μH while the measured value is 1.45 μH. Since the electromagnetic energy integration method is fairly accurate, based on finite-element calculation theory, using Equation (10) is preferable here when the mutual inductance is small and comparable to wiring inductance. Comparing the simulated and measured mutual inductance results, the simulation model shown in Figure 5 is also preliminarily verified.

B. Vehicle is Aligned with One Ground-Side Coil

This subsection focuses on EM safety investigation when EV is positioned above one charging pad, as shown in Fig. 5 (a). Figure 6 presents the EM-field distribution when a vehicle is aligned or misaligned with one ground-side coil, corresponding to scenarios in Fig. 2 (a) and (c). The EM-field distribution corresponding to scenarios in Fig. 2 (a) and (c) are presented in Fig. 7, respectively. From Fig. 7, it is certain that the misalignment leads to a field distortion towards the misaligned direction, as shown in Fig. 7 (b) compared to Fig. 7 (a).

According to SAE Standard J2954 [18], the maximum allowed misalignment corresponding to Fig. 2 (c) is set as 100 mm. The default ferrite backplate shielding mentioned in SAE Standard J2954 is also provided in Fig. 6 as a comparison baseline. In Fig. 6, it is observed that the proposed shielding design mentioned in Fig. 5 (a) demonstrates greatly effective mitigation of EM emission for both aligned and 100 mm misaligned cases. All stray fields over 1 m can be maintained below 15 μT, which would be safe even for people with implantable medical devices.

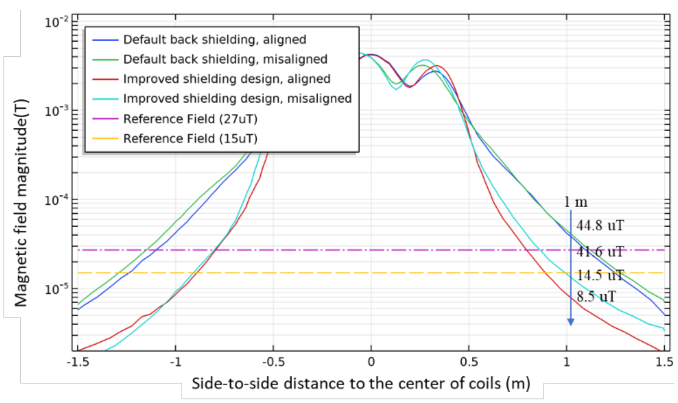


Fig. 6. Simulated EM-field distribution results along side-to-side direction when vehicle is aligned with one ground-side coil.

To determine the preferred ferrite dimension considering the tradeoffs between shielding effectiveness and ferrite amount usage, sensitivity analysis in the side-to-side (width) ferrite extension, as shown in Fig. 5 (a), is also conducted, with results presented in Fig. 8. Since side-to-side extension of ferrites is designed mainly for the purpose of ensuring EM safety in case of misalignment, the studies with results of Fig. 8 are for the misaligned case, corresponding to that in Fig. 2 (c). It is observed that the shielding effectiveness is nearly linear with the increase of ferrite width, from 16 μT of 100 mm ferrite width extension to 11.5 μT of 250 mm extension. In general, the shielding improvement is not very significant considering the ferrite usage increase. For a compact and lightweight design, ferrite width extension of 150 mm is selected here, with 14.5 μT achieved at 1 m away from the coil center, which is also aligned with the light-blue result shown in Fig. 6.

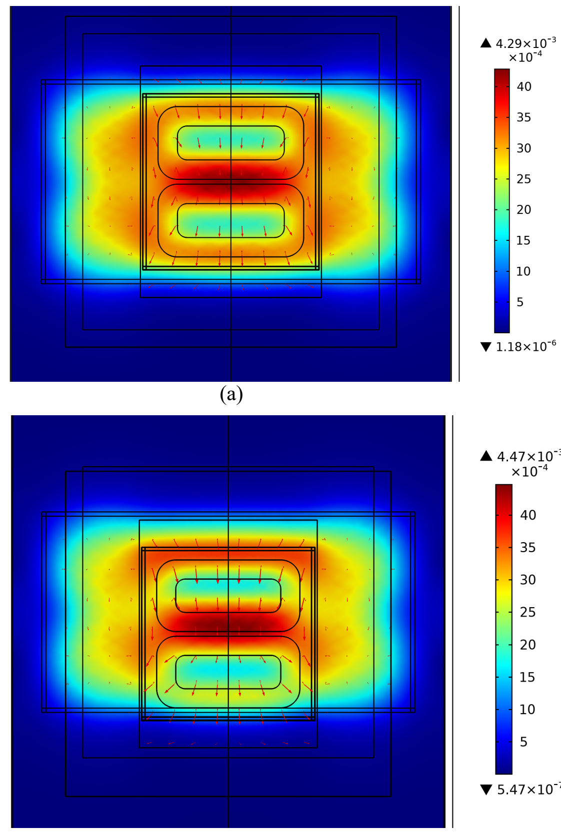


Fig. 7. EM-field distribution when (a) EV and charging pad are aligned and (b) EV has side-to-side misalignment with charging pad.

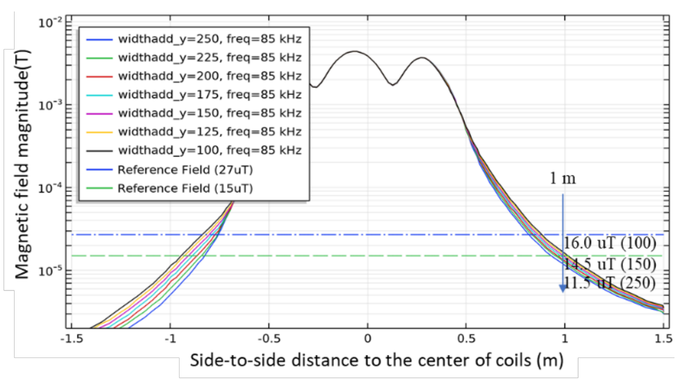
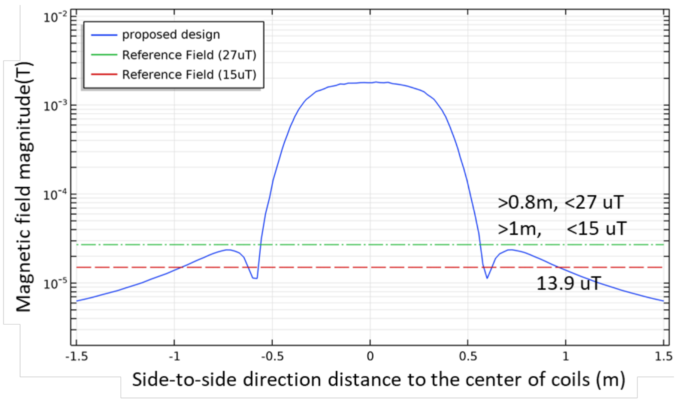


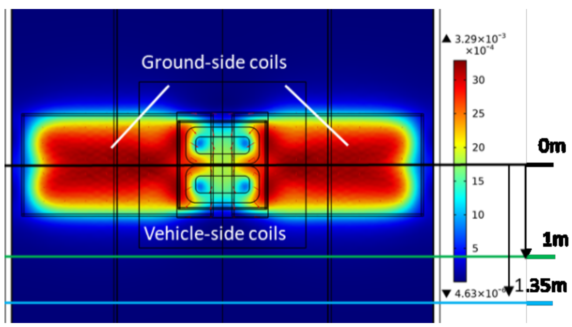
Fig. 8. Sensitivity analysis with different side-to-side extention widths of vehicle-side ferrite backing plate.

C. Vehicle is Positioned between Two Ground-Side Coils

Figure 9 presents the simulated (a) EM distribution along side-to-side direction, (b) two-dimensional (2D) plate EM field, and (c) EM field along driving direction with a side-to-side offset distance of 1 and 1.35 m, respectively. These correspond to the scenario of Fig. 2 (b) and model Fig. 5 (b) when a vehicle is positioned between two ground-side coils. From Fig. 9 (a), it is observed that all fields along side-to-side direction over 0.8 m are below 27 μT. The emission field at 1 m is 13.9 μT, which is below 15 μT. It is proven that side-to-side field emission for this scenario, where a vehicle is between two ground coils, is not a significant concern.



(a)



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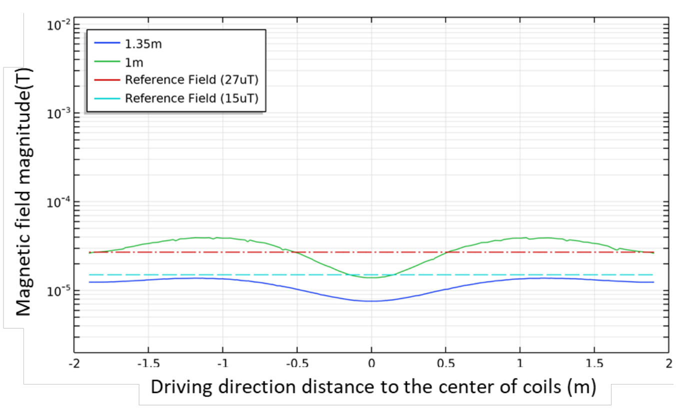

(c)

Fig. 9. (a) EM field along side-to-side direction (b) 2D EM-field distribution and (c) EM field along driving direction with a side-to-side offset distance of 1 and 1.35 m, respectively.

However, there is an interesting phenomenon when considering EM-field distribution in the driving direction, with results shown in Fig. 9 (b) and (c). In this case, the field-distribution trend is different from static WPT [5], [24] results mentioned in Subsection V.B, as well as that of shown in Figure 9 (a). In this case, the peak EM-field spot is adjacent to the ground-side coil center, instead of a vehicle-side coil center in the middle.

As shown in the blue lines of Figure 9 (c), all fields over 1.35 m away are maintained below 15 µT by using the proposed shielding design shown in Fig. 5 (b). However, the peak fields will exceed 27 µT when 1 m away, as shown in the green lines. In this case, the peak emission fields are mainly due to the ground-side coils' standalone contribution, rather than a combination of both vehicle-side and ground-side coils. Since it will be costly to further increase the usage of ferrites to achieve better shielding effectiveness, a compact but effective shielding design, as shown in Fig. 5, is adopted in this study as a more optimal shielding solution. This option still works well given the assumption of a 1.35 m safety-distance criteria discussed in Section II for dWPT.

VI. Conclusion and Discussion

This paper investigates EM safety of dWPT at 200 kW and considers different dynamic scenarios when the EV is aligned or between charging pads along the electrified roadway. Quasi-dynamic simulation models are developed for the analysis, considering all electromagnetic transients, but not the speed of the EV motion. Based on the preliminary assumption of 1.35 m safety-distance criteria discussed in Section 2 for dWPT, EM safety under several typical dWPT scenarios can be secured by using the proposed shielding design. Currently, the full-size high-power dWPT is under development. The hardware development and evaluation progress will be presented later in our future work.

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