

Generalized Models on Self-Decoupled Dual Pick-up Coils for Large Lateral Tolerance

Su Y. Choi, *Student Member, IEEE*, Seog Y. Jeong, *Student Member, IEEE*, Eun S. Lee, *Student Member, IEEE*, Beom W. Gu, *Student Member, IEEE*, Sung W. Lee, *Member, IEEE*, and Chun T. Rim, *Senior Member, IEEE*

Abstract—Self-decoupled dual pick-up coils for large lateral tolerance and low electromagnetic field for pedestrians are proposed. Analytical models are developed that are applicable to any self-decoupled coils, regardless the coil types such as single/dual pick-ups and core/coreless coils. An optimum decoupling distance between adjacent pick-up coils is determined and found to be independent of the existence of a core plate. Maximum load power over a large lateral tolerance is obtained for the optimum decoupling distance. The proposed models are so general that they can be applied to any self-decoupled pick-up coils for stationary charging and dynamic charging systems. Moreover, the self-decoupled coils are compatible with any compensation method such as serial, parallel, and serial-parallel. A prototype system of 1.5 kW and $Q = 60$ for roadway powered electrical vehicles was implemented and showed fairly good agreements with the theoretical models and simulations. The measured lateral tolerance was 90 cm, which is about 1.5 times of the coil width.

Index Terms—Dual pick-up coils, inductive power transfer systems (IPTS), lateral displacement, lateral tolerance, roadway powered electric vehicles (RPEV), self-decoupling.

I. INTRODUCTION

ENVIRONMENTAL pollution and the exhaustion of oil resources are becoming serious issues, where conventional vehicles account for one of the largest portions of the pollution. As a solution, electric vehicles (EVs), such as hybrid electric vehicles (HEVs), plug-in HEV, and pure EV, have been developed, but they have not been widely used due to battery problems, namely, high cost, heaviness, large installation space, and frequent charging due to low energy capacity. In order to mitigate the battery problems, roadway powered electric vehicles (RPEVs) using inductive power transfer systems (IPTSs) have been proposed [1]–[21]. By virtue of the IPTS, the RPEV can

be powered during its operation, and it can be free from the battery problems. In general, the IPTS adopts resonant circuits to maximize the power transfer, which is a challenging design issue due to the static and dynamic characteristics of the resonant circuits and IPTS; however, the dynamic and static behaviors of the IPTS can be characterized by using phasor transformation [22]–[25].

In the IPTS for RPEVs, a sufficient air-gap between a power supply rail and pick-up coils, a large lateral tolerance between the centers of the power supply rail and pick-up coils, and a low electromagnetic field (EMF) for pedestrians are important design issues. In order to meet the three requirements, a narrow-width I-type power supply rail with alternative magnetic poles was proposed [11], [12]. However, the width of the pick-up coils should be very large in order to get a large lateral tolerance, which results in a higher EMF from the pick-up coils than permitted by the ICNIRP guidelines for pedestrians [26]. Moreover, the inductance of the pick-up coils becomes large as its width increases, which leads to a high voltage stress on compensation capacitors in resonant condition and a narrow 3 dB bandwidth due to the higher quality factor.

As a remedy to these problems, a dual pick-up coil with active EMF cancel coils for an I-type power supply rail was suggested [1]–[3], where the active EMF cancel coils are wound in the opposite direction of the dual pick-up coil to lower the EMF for pedestrians. The dual pick-up coil [14], in which two pick-up coils are aligned along with the moving direction (y), as shown in Fig. 1(a), has an inherently low EMF for pedestrians and a strong magnetic coupling between the power supply rail and pick-up coils compared to a single pick-up coil. Although the dual pick-up coil can mitigate the EMF level, the lateral tolerance has not been improved yet.

In order to increase the lateral tolerance, a set of laterally displaced two pick-up coils, in which two coils overlap each other, as shown in Fig. 1(b), may be used [10]. In this case, each coil achieves its peak power when it is aligned with the center of a power supply rail, as shown in Fig. 2(a). Therefore, it is expected that a larger lateral tolerance can be obtained if a higher load power from each coil is appropriately selected, as shown in Fig. 2(b).

Throughout the development of the IPTS [10], however, the peak power was obtained only at the overlapped area, and in practice, the power was abruptly dropped to zero out of this area, which unexpectedly resulted in a much smaller lateral tolerance, as shown in Fig. 2(c). The lateral tolerance, which is defined in this paper as the allowable lateral displacement from the center to give less than -3 dB load voltage, can be roughly

Manuscript received August 8, 2014; revised December 25, 2014; accepted January 27, 2015. Date of publication February 18, 2015; date of current version July 10, 2015. This work was supported by Center for 3I Innovative Power Reactor of Department of Nuclear and Quantum Engineering of KAIST (20121610100030), by the Nuclear Power Core Technology Development Program of the Korea Institute of Energy Technology Evaluation and Planning, and a grant from the Ministry of Trade, Industry & Energy, Republic of Korea (21A20130012538). This paper was presented in part at the ECCE-Asia 2014. Recommended for publication by Associate Editor J. M. Miller.

S. Y. Choi, S. Y. Jeong, E. S. Lee, B. W. Gu, and C. T. Rim are with the Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Technology, Daejeon 305-755, Korea (e-mail: suchoi@kaist.ac.kr; seogyong@kaist.ac.kr; eunsoo86@kaist.ac.kr; kbw755@kaist.ac.kr; ctrim@kaist.ac.kr).

S. W. Lee is with Samsung Electronics, Suwon 443-371, South Korea (e-mail: leesungwoo1982@gmail.com).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TPEL.2015.2399938

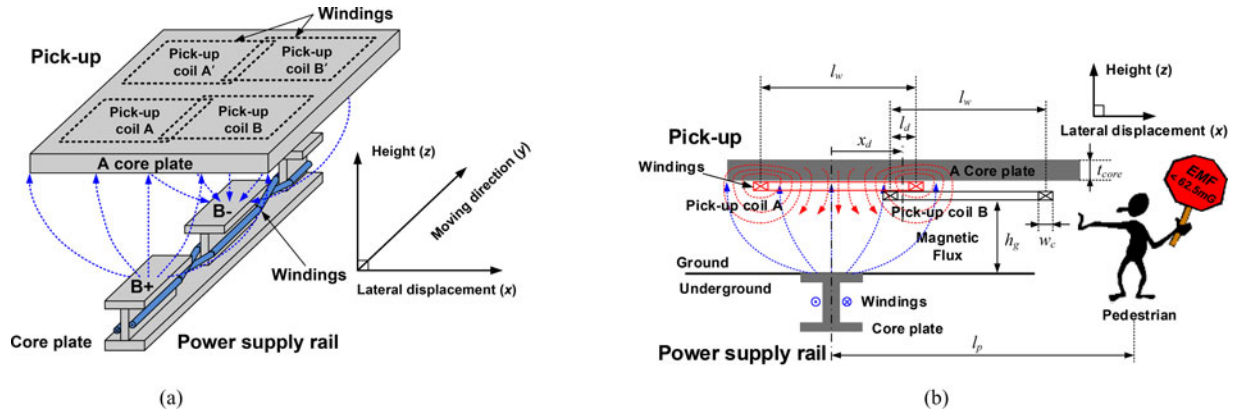


Fig. 1. Proposed self-decoupled dual pick-up coils for a large lateral tolerance and low EMF level on an I-type power supply rail example. (a) Bird's eye view. (b) Front view, where the pick-up coils A-A' are coupled with the power supply rail but the pick-up coils B-B' are not.

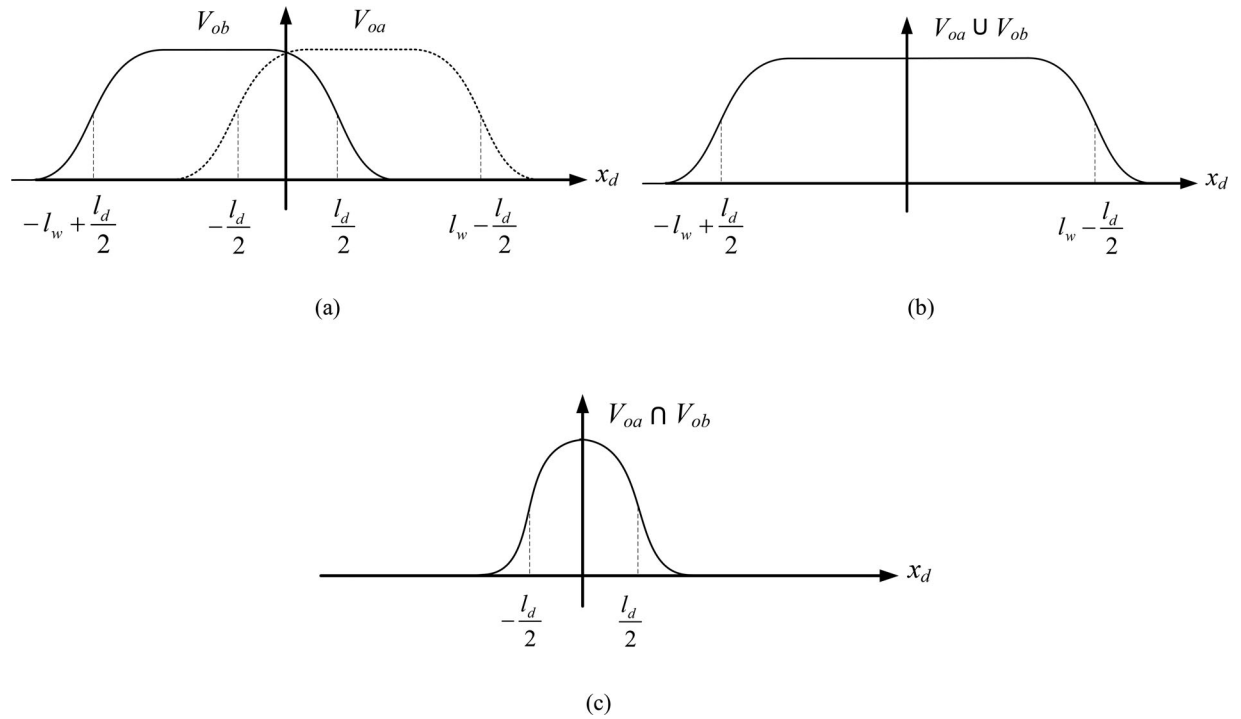


Fig. 2. Load voltage profile over the lateral displacement. (a) Voltage of each dual pick-up coil. (b) Expected large lateral tolerance. (c) Observed small lateral tolerance.

estimated from Fig. 2(b) and (c) as follows:

$$l_{t, \text{decoupled}} \cong 2l_w - l_d \text{ for } V_{oa} \cup V_{ob} \quad (1a)$$

$$l_{t, \text{coupled}} \cong l_d \text{ for } V_{oa} \cap V_{ob} \quad (1b)$$

where (1a) is the theoretical goal to be achieved in this paper and (1b) is the experimental result has been obtained so far. One of the merits of the laterally displaced two pick-up coils, called in this paper a “self-decoupled pick-up coil,” is its low self-inductance of each coil for a given width of the pick-up. Without the self-decoupled pick-up coil, a pick-up coil with a large width should be used, resulting in high self-inductance.

In this paper, the phenomenon of the small lateral tolerance for the two overlapped pick-up coils, as shown in Fig. 2, is thoroughly explained and a self-decoupled dual pick-up coil is first proposed as a solution to both the large lateral tolerance and the low self-inductance. The concept of a self-decoupled coil itself is not new and was first introduced in the field of magnetic resonance imaging [27] two decades ago. The concept was recently applied to the EV stationary charging systems [28], [29], where a self-decoupled pick-up coil was used to enlarge the lateral tolerance. However, thus far, no analytical model for the self-decoupled pick-up coil has been given. Hence, generally applicable theoretical models for the self-decoupled coil are proposed in this paper.

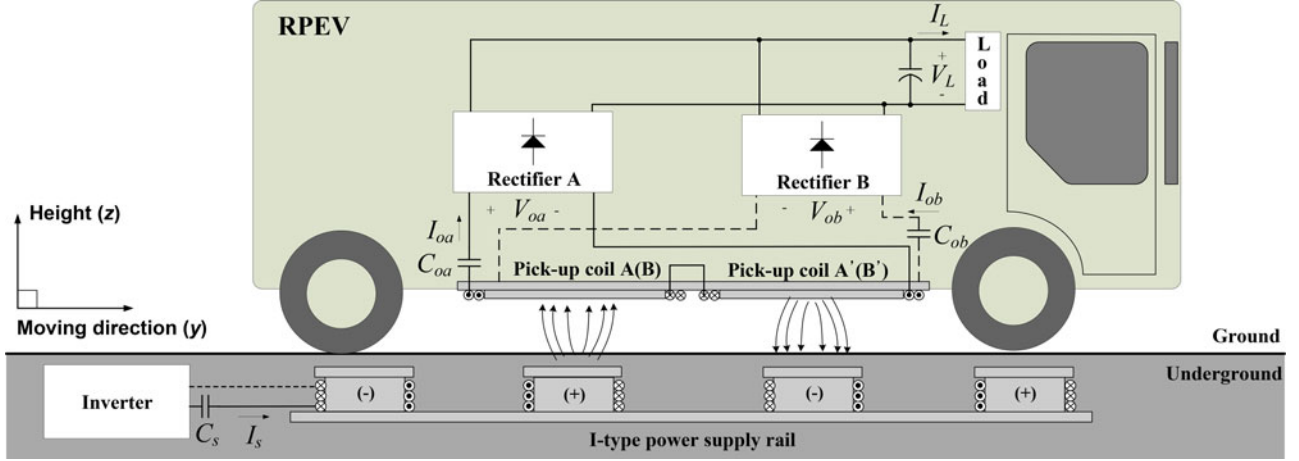


Fig. 3. Side view of the IPTS for RPEV, adopting the proposed self-decoupled dual pick-up coil sets. Voltages and currents in the circuit are rms values in the steady state.

As an example, the self-decoupled dual pick-up coils for RPEV, as shown in Fig. 1(a), are analyzed, simulated, and experimentally verified in this paper. Thus, an optimum decoupling distance is systematically determined that can be generally applied to any self-decoupled coil regardless the coil types such as single/dual, stationary/dynamic charging, and core/coreless. Moreover, the proposed self-decoupled coils are compatible with any compensation method, including serial, parallel, and serial-parallel. By virtue of the proposed coil, not only a large lateral tolerance but also a large air gap can be achieved. In addition, a low voltage stress of compensation capacitors and a low EMF for pedestrians can be obtained without the use of active EMF cancel coils, as shown in Fig. 1(b). The equivalent circuits and mathematical models for the self-decoupled dual pick-up coil are newly proposed for both cases of with and without a core plate, where the finite-width magnetic mirror theory [30] is adopted to reflect the effect of a core plate on magnetic inductance.

II. SELF-DECOUPLED DUAL PICK-UP COILS WITH AN I-TYPE POWER SUPPLY RAIL

A. Overall Configuration of the Proposed Pick-up Coils

The IPTS for RPEV makes it possible to get the required power from a power supply rail while it is moving, as shown in Fig. 3. The IPTS includes two subsystems [15]: one is the roadway subsystem to provide power for the RPEV and consists of a line frequency rectifier, a high frequency inverter, a primary capacitor bank, and a power supply rail; the other is the on-board subsystem for receiving the required power from the roadway subsystem, which includes pick-up coils, a secondary capacitor bank, a high frequency rectifier, and a regulator.

The dual pick-up coil A-A' overlaps the dual pick-up coil B-B', as shown in Figs. 1 and 3, where an I-type power supply rail is displaced in the underground. Each dual pick-up coil is resonated and rectified separately and is then connected in parallel to produce the highest dc output voltage for the load, as shown in Fig. 3. The rectified dc output voltage may be

connected in series; however, the conduction loss attributing from both dual pick-up coils becomes doubled in this case.

As shown in Fig. 4, there are eight magnetic couplings (magnetizing inductances) between the coils of the proposed IPTS:

- 1) the couplings between the power supply rail and dual pick-up coil A-A' (L_{ma});
- 2) the couplings between the power supply rail and dual pick-up coil B-B' (L_{mb});
- 3) the coupling between coils A and B ($L_m/2$);
- 4) the coupling between coils A' and B' ($L_m/2$);
- 5) the coupling between coils A and A';
- 6) the coupling between coils B and B';
- 7) the coupling between coils A and B';
- 8) the coupling between coils B and A'.

For simplicity, the internal coupling cases of dual pick-up coils 5 and 6 will be regarded as a lumped coil, the cross coupling cases 7 and 8 will not be separately modeled, and the effect of lateral displacement on the coupling changes of L_{ma} , L_{mb} , and L_m will be highly focused on in this paper.

Throughout this paper, it is assumed that there is neither tilt nor misalignment between the EV and power supply rail except for a lateral displacement. It is also assumed that each pick-up coil is located just above the center of each pole of the power supply rail in moving direction (y), as shown in Fig. 3. All of the circuit parameters of each dual pick-up coil are assumed to be the same, and the circuit is assumed to be operating in the steady state.

B. Problems of the Nondecoupled Pick-up Coils

As the center of the overlapped pick-up coils A and B (A' and B' as well) is well aligned with the power supply rail, i.e., $x_d = 0$, the induced voltage of the pick-up coil A is exactly the same as that of the pick-up coil B (that of A' and that of B' as well); hence, there is no coupling effect between the pick-up coils A and B (A' and B' as well) due to the symmetrical circuit configuration. If this is not this case, as shown in Fig. 1(b), the induced voltages and resonating currents of the pick-up coils A

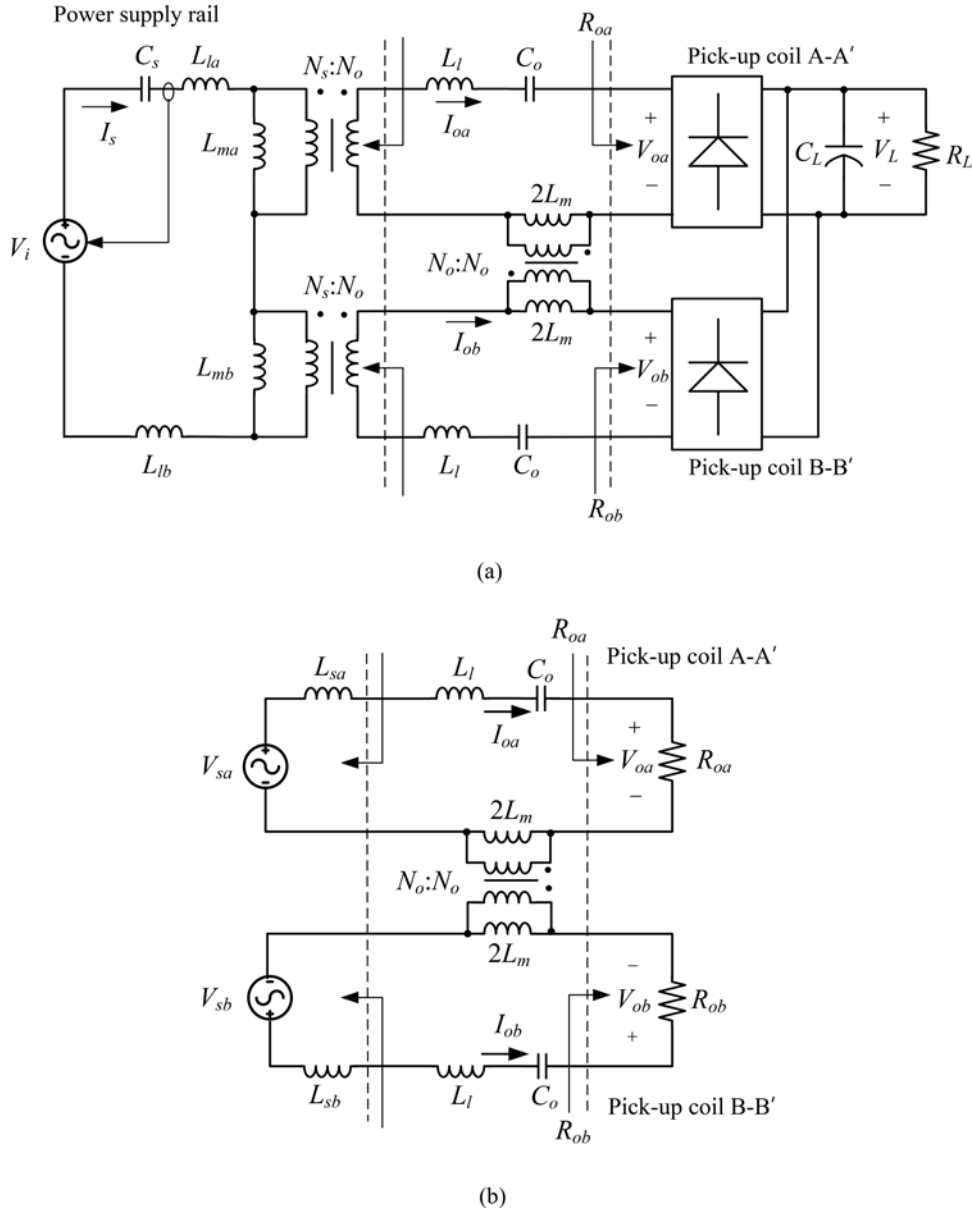


Fig. 4. Circuit diagrams for the proposed IPTS, considering the magnetic coupling of the power supply rail and each dual pick-up coil, where the dual pick-up coils are magnetically coupled to each other. (a) Explicit transformer circuit. (b) Simplified Thevenin equivalent circuit.

and B (A' and B' as well) are different from one other, resulting in a coupling current between the pick-up coils A and B (A' and B' as well).

As shown in Fig. 3, a series-series compensation is used in this paper as an example. Note that the proposed self-decoupled model is valid for other compensation schemes as well, which will be explained in this paper. A circuit diagram for the proposed IPTS is suggested, as shown in Fig. 4(a), considering the magnetic coupling between the power supply rail and each dual pick-up coil (denoted as L_{ma} and L_{mb} , respectively), where the dual pick-up coils are magnetically coupled to each other (denoted as L_m). As widely adopted in the RPEV [10]–[15], the source current I_s is assumed to be constant, as they are regulated by the inverter. As shown in Fig. 4(b), the source-side circuit

can be simplified as Thevenin equivalent voltage sources and inductors [11]–[15] as follows:

$$V_{sa} = j\omega_s L_{ma} I_s n \quad (2a)$$

$$V_{sb} = j\omega_s L_{mb} I_s n \quad (2b)$$

$$L_{sa} = n^2 L_{ma} \quad (2c)$$

$$L_{sb} = n^2 L_{mb} \quad (2d)$$

$$\therefore n \equiv N_o/N_s. \quad (2e)$$

where V_{sa} and V_{sb} are the induced voltages, represented in phasor form, for the dual pick-up coils A-A' and B-B', respectively. n is the turn ratio of the power supply rail N_s and a dual pick-up coil N_o , and L_l is the leakage inductance of a dual pick-up

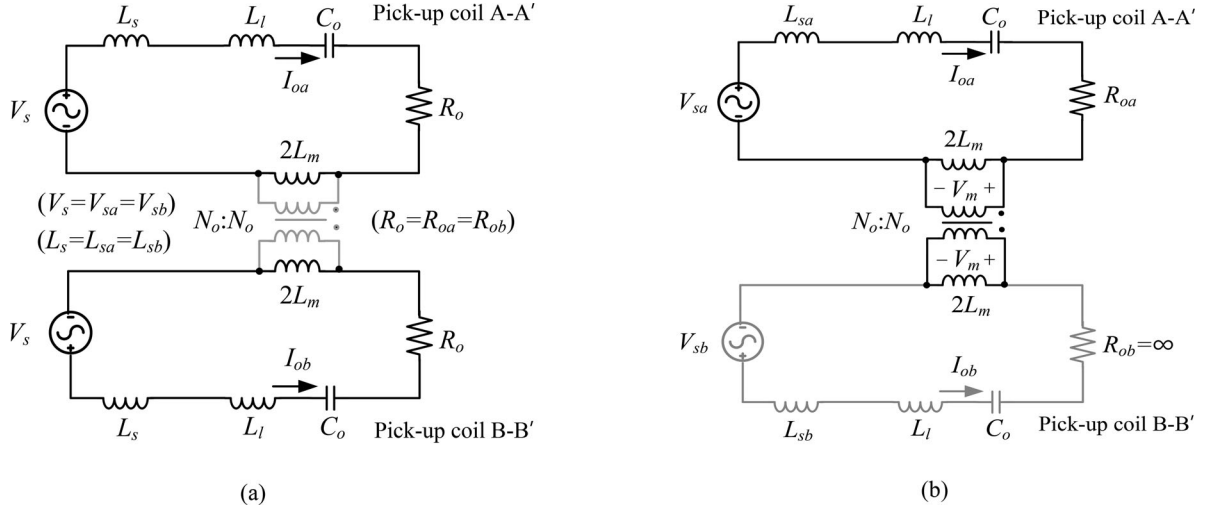


Fig. 5. Equivalent circuits of Fig. 4(b) when the power supply rail is (a) well-aligned ($|x_d| < l_d/2$) or (b) misaligned ($|x_d| > l_d/2$) with the pick-up.

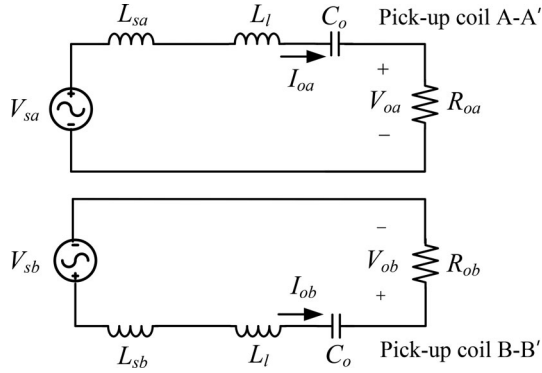


Fig. 6. General equivalent circuit of Fig. 4(b) when the pick-up coils are self-decoupled from each other, i.e., $L_m = 0$.

coil. C_o is the series compensation capacitor for pick-up side resonance. The diode rectifiers are also simplified as equivalent resistances R_{oa} and R_{ob} , respectively, considering the fundamental components of the voltages and currents of the rectifiers as follows [31], [32]:

$$R_{oa} \equiv \frac{V_{oa}}{I_{oa}} = \frac{2\sqrt{2}}{\pi} \frac{V_L}{I_{oa}} \quad (3a)$$

$$R_{ob} \equiv \frac{V_{ob}}{I_{ob}} = \frac{2\sqrt{2}}{\pi} \frac{V_L}{I_{ob}}. \quad (3b)$$

As shown in Fig. 4, the magnetizing inductance of the dual pick-up coils L_m is segmented into two $2L_m$ for each side so that each pick-up coil looks symmetrical. Also note that L_{sa} and L_{sb} as well as V_{sa} and V_{sb} are variable as L_{ma} and L_{mb} change along the lateral displacement, while L_l and L_m are nearly unaffected.

Now, let us examine the behavior of the circuit of Fig. 4(b) for both the aligned and misaligned cases of the pick-up, as shown in Fig. 5. Depending on the lateral displacement, the induced voltages V_{sa} and V_{sb} and circulating currents I_{oa} and I_{ob} vary, which results in the variation of the equivalent resistances

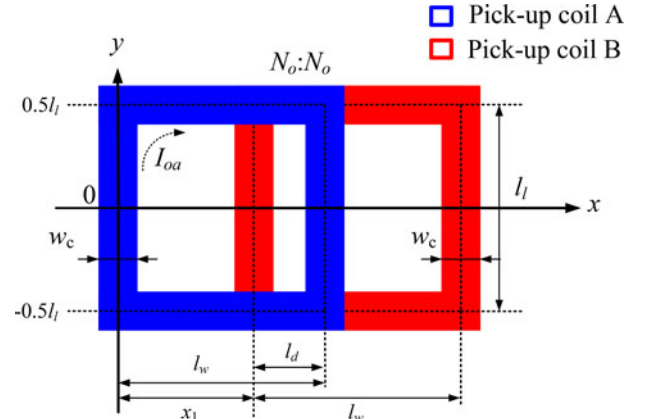


Fig. 7. Top view of the coupled pick-up coil model without a core plate.

of (3a) and (3b). When the pick-up is exactly aligned with the power supply rail, all the circuit parameters and variables are symmetrical, as shown in Fig. 5(a), where the equivalent resistance becomes as follows:

$$R_o \equiv \frac{V_{oa}}{I_{oa}} = \frac{8}{\pi^2} \frac{V_L}{I_L/2} = \frac{16}{\pi^2} R_L. \quad (4)$$

Then, no current flows between the transformer, which results in two independent circuits whose resonant frequency ω_{r0} is determined as follows:

$$\omega_{r0} = \frac{1}{\sqrt{(L_s + 2L_m + L_l)C_o}} \text{ for } x_d = 0. \quad (5)$$

As shown in Fig. 5(b), when the pick-up is misaligned so that the $V_{sb} = V_m$ condition may be eventually met, the circulating current I_{ob} becomes zero, which results in $R_{ob} = \infty$, as identified from (3b). Under this condition, the resonant frequency ω_{r1} is determined differently from (5) as follows:

$$\omega_{r1} = \frac{1}{\sqrt{(L_{sa} + L_m + L_l)C_o}} \text{ for } |x_d| \gg l_d/2. \quad (6)$$

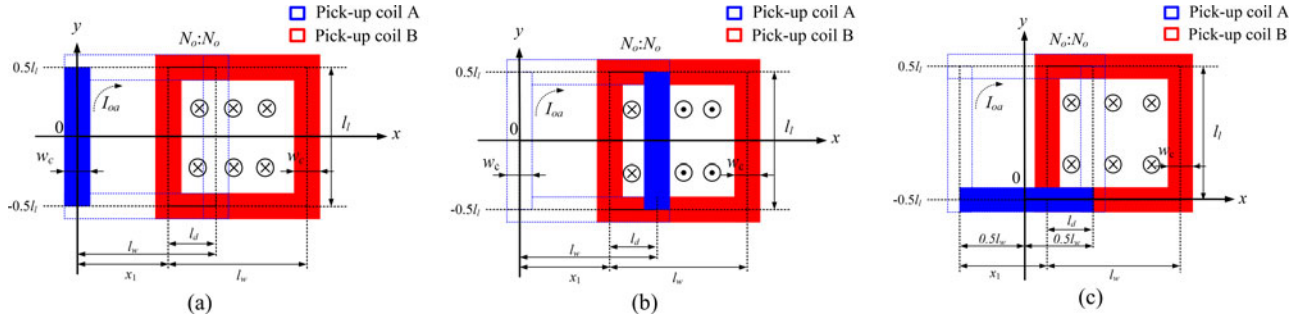


Fig. 8. Intersecting magnetic flux generated from each side of coil A. (a) ϕ_1 for the left side. (b) ϕ_2 for the right side. (c) ϕ_3 for the down side.

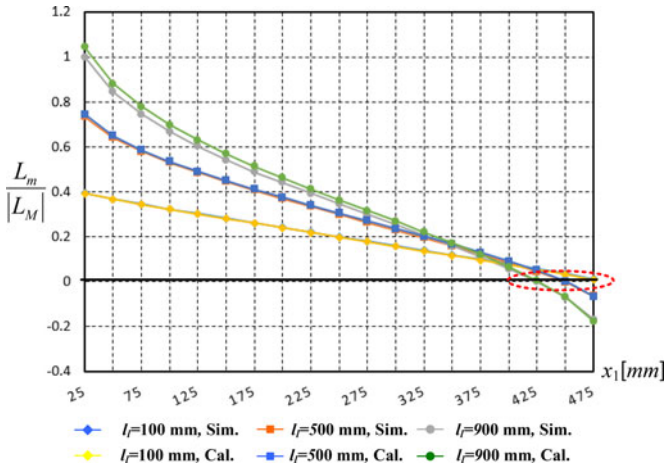


Fig. 9. Three-dimensional FEA simulated L_m without a core plate and the calculated L_m for various lengths l_l of the pick-up coils A and B. The L_M is the maximum mutual inductance between the two pick-up coils for $l_l = 90$ cm, $l_w = 50$ cm, and $x_1 = 2.5$ cm without a core plate.

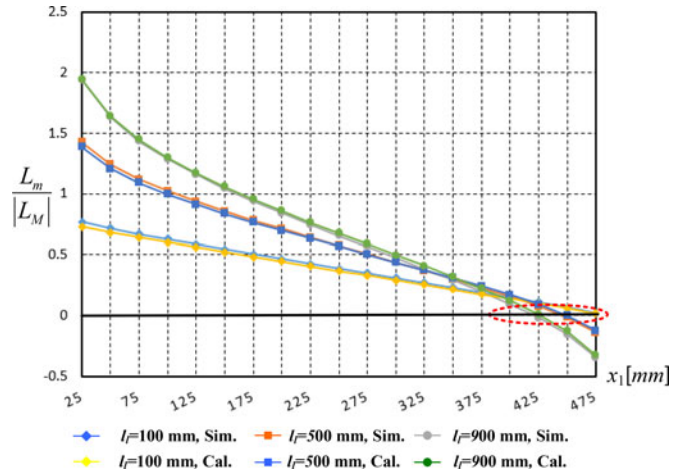


Fig. 11. Comparison of the 3-D FEA simulated L_m with a core plate ($l_a = 120$ cm, $l_b = 120$ cm, $\mu_r = 2000$) with the calculated L_m with a core plate for various length l_l of pick-up coils A and B. The L_M is the maximum of L_m without a core plate for $l_l = 90$ cm, $l_w = 50$ cm, and $x_1 = 2.5$ cm.

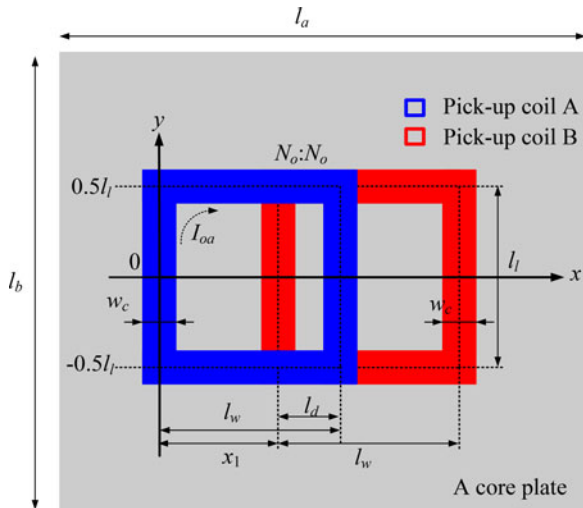


Fig. 10. Top view of the decoupled pick-up coil model with a core plate.

It is clearly identified from the two specific cases of (5) to (6) that the misaligned resonant frequency of a dual pick-up coil ω_{r1} may deviate from the operating frequency, which is normally tuned to the central resonant frequency ω_{r0} . In a more generalized misaligned case in which each A-A' coil and B-B'

coil has different resonant frequency, the analysis of Fig. 5(b) is not straightforward. It is evident, however, that the power delivery for this misaligned case is much less than the aligned case because of the less induced voltages as well as the reduced circulating currents due to the mistuned resonating circuits. In practice, the delivered power sharply drops when the resonating circuit gets out of resonance. In this way, the load voltage profile becomes very narrow for this nondecoupled pick-up case where L_m is not zero, as shown in Fig. 2(c).

Even though the previous discussions on the nondecoupled pick-up coils have been in regards to the series-series compensation example, the coupling effect mentioned earlier is valid for any compensation scheme, including series-parallel and parallel-parallel. This is because the misalignment of the pick-up causes the detuning of resonating circuits, regardless of the compensation scheme. Moreover, this misalignment effect is also valid for a serially connected output case, even though it is shown only for the parallelly connected case of Figs. 3 and 4 in this paper.

A complete analysis of Fig. 4(b) for the misaligned nondecoupled case is not provided here, though it is not impossible, because it is not very useful in practice. Instead, the case of the self-decoupled in which L_m is zero will be highly focused, which is quite useful in practice.

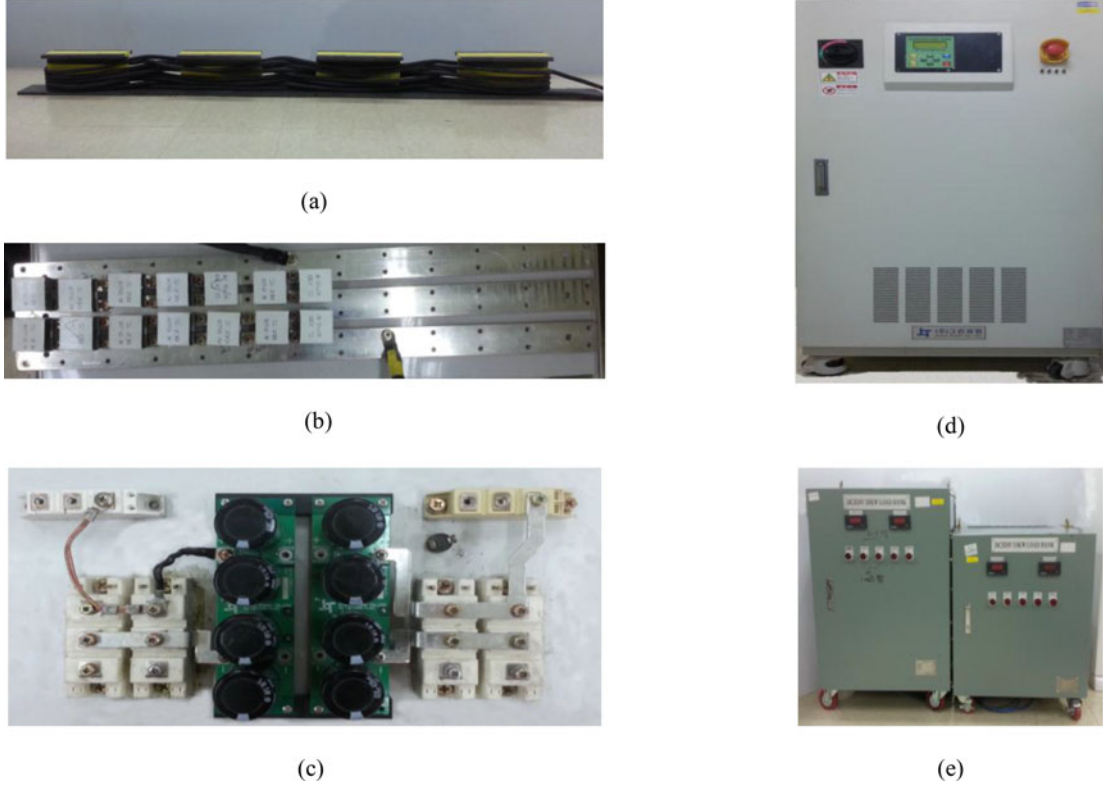


Fig. 12. Experimental IPTS set. (a) Power supply rail. (b) Capacitor bank using the KEMET film capacitors. (c) Rectifiers. (d) Inverter. (e) Load bank.

TABLE I
EXPERIMENTAL CONDITIONS OF THE IPTS

Parameters	Values	Parameters	Values
I_s	10 A	h_g	10 cm
N_s	10	t_{core}	1 cm
f_s	20 kHz	μ_r	2000

C. Self-Decoupled Single Pick-up Coil Set Without a Core Plate

For obtaining a sufficient power regardless of the pick-up misalignment, there are generally two possible solutions: one is to use an adaptive frequency control of the inverter to ensure the pick-up is always tuned and another is to minimize the difference between ω_{r0} and ω_{r1} of (5) and (6). In practice, the former is hardly used for RPEVs because many vehicles with different resonant conditions may be on a power supply rail. The latter, however, is easy to implement if L_m is appropriately nullified. The condition “ $L_m = 0$ ” is called “self-decoupled” in this paper, and the resonant frequencies of the pick-up become as follows:

$$\omega_{r0} = \frac{1}{\sqrt{(L_s + L_l)C_o}} \text{ for } x_d = 0 \text{ and } L_m = 0 \quad (7a)$$

$$\omega_{r1} = \frac{1}{\sqrt{(L_{sa} + L_l)C_o}} \text{ for } |x_d| \gg l_d/2 \text{ and } L_m = 0 \quad (7b)$$

$$\rightarrow \omega_r \equiv \omega_{r0} \cong \omega_{r1} = \frac{1}{\sqrt{(L_s + L_l)C_o}} \text{ if } L_s \cong L_{sa} \text{ and } L_m = 0. \quad (7c)$$

Comparing (7a) with (7b), it is found from (7c) that there is little frequency difference between the aligned and misaligned cases if only $L_s \cong L_{sa}$ condition is met. This remaining condition for a large lateral tolerance will be verified by experiments in this paper.

Thus, a general equivalent circuit for the proposed self-decoupled dual pick-up coils is obtained, where two independent circuits operate regardless of misalignment, as shown in Fig. 6.

In this paper, L_m is nullified by adjusting the distance x_1 between two pick-up coils, as shown in Fig. 7. In order to develop a preliminary analytic model, only the single self-decoupled pick-up coil A-B without a core plate, instead of the dual pick-up coils A-A' and B-B' of Fig. 1, is considered at the moment, where two coplanar rectangular windings of a width w_c overlap each other with a distance of l_d , which is similar with double-D (DD), bipolar (BP), and tripolar (TP) coils [28], [29], [33].

In order to determine an optimum distance x_1 for $L_m = 0$, the L_m is analytically obtained as follows:

$$L_m \equiv \frac{N_o \phi_m}{I_{oa}} \quad (8a)$$

$$\therefore \phi_m = \phi_1 + \phi_2 + \phi_3 + \phi_4. \quad (8b)$$

Because the super position theorem can be applied to the coreless case (i.e., free space) of Ampere's law, the total mutual

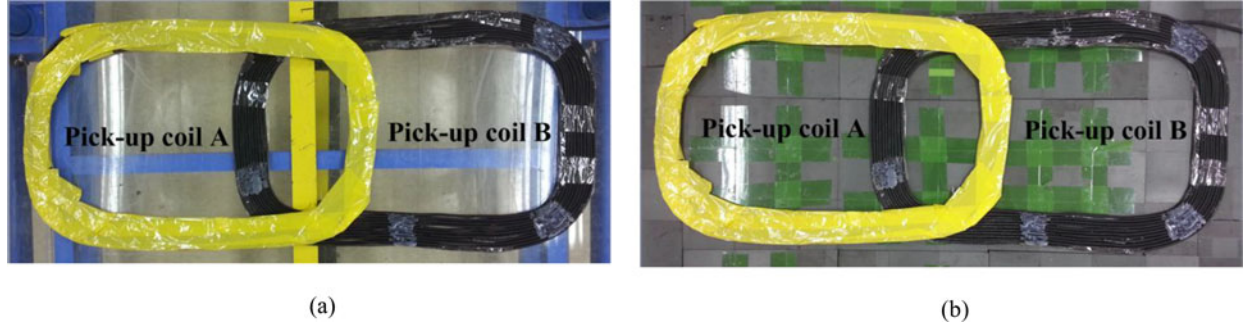


Fig. 13. Experiment set of the self-decoupled single pick-up coils A and B. (a) Without a core plate. (b) With a core plate.

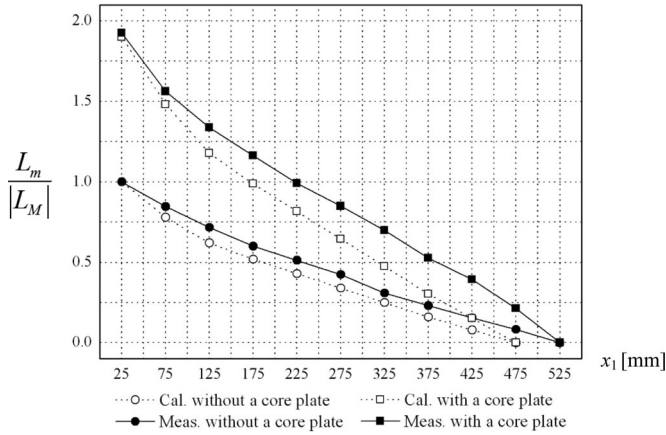


Fig. 14. Measured mutual inductance L_m between pick-up coils A and B for various distances with/without a core plate. The L_M is the maximum L_m for $l_l = 36$ cm, $l_w = 62$ cm, and $x_1 = 2.5$ cm without a core plate.

magnetic flux ϕ_m is the sum of the ϕ_1 , ϕ_2 , ϕ_3 , and ϕ_4 , which are the intersecting magnetic fluxes to coil B, induced from the left, right, bottom, and top of the pick-up coil A, respectively, as shown in Fig. 8. The magnetic flux induced from the bottom side of the pick-up coil A is equal to that from the top side, so the top side case is not shown in Fig. 8. Then, the total mutual magnetic flux becomes

$$\phi_m = \phi_1 + \phi_2 + 2\phi_3 \quad \because \phi_3 = \phi_4. \quad (9)$$

In order to make L_m be “0,” the ϕ_m should be “0” by changing the pick-up coil B x_1 .

Assuming that the winding width is much smaller than the coil width, i.e., $w_c \ll l_w$, the coil winding can be regarded as a thin wire; hence, the ϕ_1 can be approximately obtained by using Biot-Savart’s law as follows:

$$\begin{aligned} \phi_1 &\cong \int_{x_1}^{x_1+l_w} \int_{-0.5l_l}^{0.5l_l} B_1(x, y) dy dx \\ &= -\frac{\mu_o N_o I_{oa}}{2\pi} \left\{ \sqrt{l_l^2 + x_1^2} + l_w \right. \\ &\quad \left. - \sqrt{l_l^2 + (x_1 + l_w)^2} - l_l \cdot \ln \frac{l_w + x_1}{x_1} \right\} \quad (10a) \end{aligned}$$

$$\begin{aligned} \because B_1(x, y) &= \frac{\mu_o N_o I_{oa}}{4\pi x} \left\{ \frac{y - l_l/2}{\sqrt{(y - l_l/2)^2 + x^2}} \right. \\ &\quad \left. - \frac{y + l_l/2}{\sqrt{(y + l_l/2)^2 + x^2}} \right\}. \quad (10b) \end{aligned}$$

In a similar way, ϕ_2 and ϕ_3 can be determined, and ϕ_m is finally obtained for $0 < x_1 < l_w$ as follows:

$$\begin{aligned} \phi_m &= -\frac{2\mu_o N_o I_{oa}}{\pi} \\ &\quad \left\{ \frac{2\sqrt{l_l^2 + x_1^2} - \sqrt{l_l^2 + (l_w + x_1)^2} - \sqrt{l_l^2 + (l_w - x_1)^2}}{2} \right. \\ &\quad \left. + \frac{l_l}{4} \cdot \ln \frac{x_1^2}{l_w^2 - x_1^2} - \frac{l_w - x_1}{2} \cdot \left(\ln \frac{l_l - 0.5w_c}{0.5w_c} - 2 \right) \right\}. \quad (11) \end{aligned}$$

In order to verify (11), a 3-D finite-element analysis (FEA) simulation for L_m was performed for $N_o I_{oa} = 1$ A-turn, $w_c = 0.5$ mm, $l_w = 50$ cm, and $l_l = 10, 50$, and 90 cm, respectively. As shown in Fig. 9, the simulated L_m is quite well matched to the analyzed L_m , which is calculated from (8a) and (11). Moreover, an optimum self-decoupling distance x_{opt} is obtained for a given coil structure, which is found to be a little less than l_w .

When $x_1 = x_{opt}$, i.e., $L_m = 0$, the resonant frequency ω_r of each pick-up coil and compensating circuit, as shown in Fig. 6, is nearly unchanged for the lateral displacement $|x_d| < l_w - l_d/2$. Therefore, the lateral tolerance can be increased from $l_d/2$ to $l_w - l_d/2$ by using the proposed self-decoupled pick-up coils. In this way, the EMF for pedestrians is greatly mitigated when the pick-up coil A is on the power supply rail because pick-up coil B, which is close to the pedestrians, is decoupled from not only the power supply rail but also pick-up coil A, which results in little circulating current and quite low EMF generation. The detail estimation of the EMF reduction highly depends on the coil configuration and the location of a pedestrian [2].

D. Self-Decoupled Single Pick-up Coil Set With a Core Plate

In this section, the discussions in the previous section will be continued with a difference in the core plate. In practice, a core plate is widely used to increase the magnetic coupling between the power supply rail and pick-up coils and to shield the RPEV

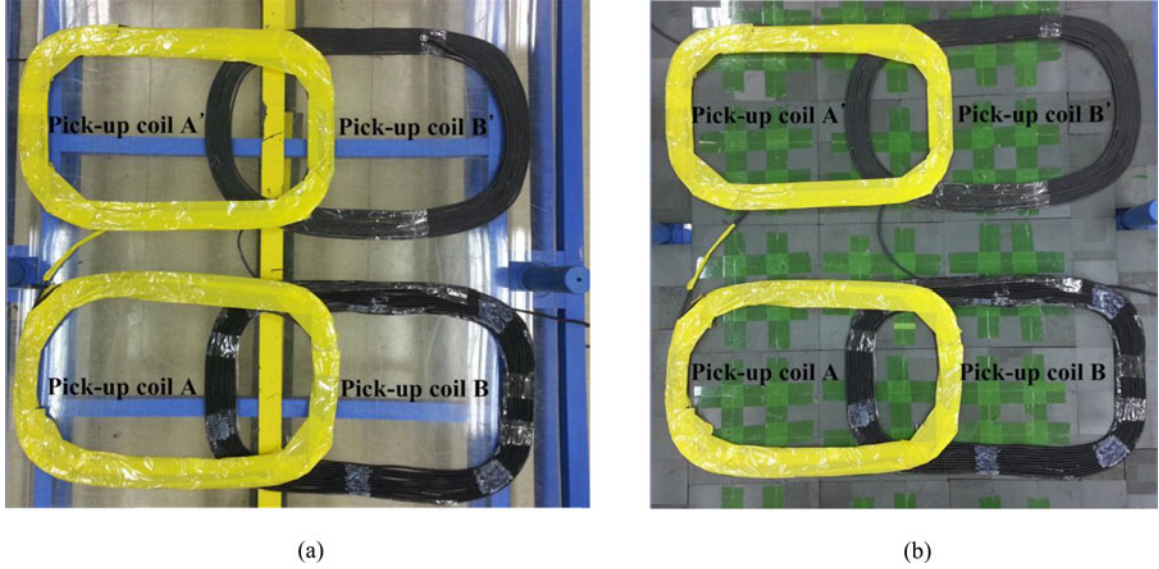


Fig. 15. Proposed self-decoupled dual pick-up coil set for experiments. (a) Without a core plate. (b) With a core plate.

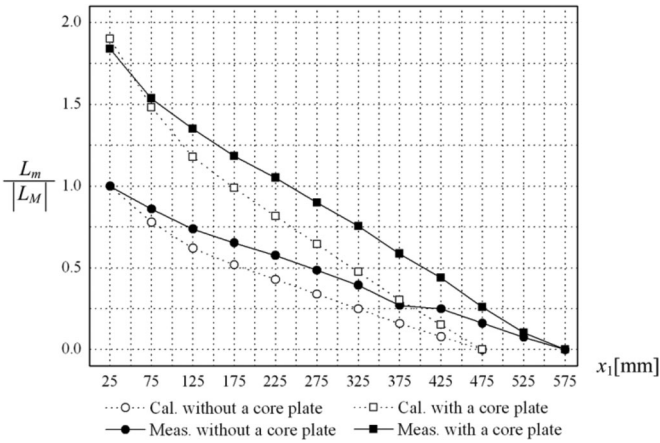


Fig. 16. Measured mutual inductances for various position of the pick-up B coils with/without a core plate. The L_M is the maximum mutual inductance between the two pick-up coils for $l_l = 36$ cm, $l_w = 62$ cm, and $x_1 = 2.5$ cm without a core plate.

from the unwanted magnetic flux leakage, as shown in Figs. 1 and 3. The core plate influences not only the coupling between the power supply rail and pick-up coils but also the coupling between pick-up coils A and B, as shown in Fig. 10. Due to the very complex interaction of the core plate, the magnetic flux induced by pick-up coil A, intersecting to pick-up coil B, is almost impossible to calculate. To solve this problem, the magnetic mirror model [24], which provides with a magnetic flux density equation of closed form when a coil winding is placed on a core plate, is adopted. According to the magnetic mirror model, the magnetic flux with an infinitely large core plate and an infinite permeability is ideally two times of the flux without the core plate. The proposed pick-up coils have a finite-size core plate ($l_a \times l_b$) with a finite relative permeability of μ_r , so the multiplying effect would be a little less than 2 by a correction factor α . Then, the total mutual magnetic flux of the with-core-plate case ϕ_{mc} is modified from the without-

core-plate case ϕ_m of (11) as follows:

$$\phi_{mc} = 2\alpha\phi_m. \quad (12)$$

In order to verify (12), a 3-D FEM simulation was done, and its results are compared with (11), as shown in Fig. 11, where α is obtained as 0.925, which gives us the best curve fitting. As expected from (12), L_m with a core plate is about two times of L_m without a core plate while the self-decoupling point x_{opt} remains unchanged. The investigation on a general relationship between the core size and α is left for further work.

III. EXPERIMENTAL VERIFICATIONS

In order to verify the proposed analytic models of the self-decoupled coils, an experimental IPTS set was fabricated, as shown in Fig. 12, where the inverter is operating at about $f_s = 20$ kHz, which is always a little bit higher than the resonant frequency f_r to guarantee the zero-voltage switching operation of the inverter [15]. The circuit parameters are appropriately selected and measured, as listed in Table I. The detailed configuration of the power supply rail specified in this paper is the same as that of [12] except the number of turns, where all the design parameters of the power supply rail are optimized by simulations and experiments.

A. Self-Decoupled Single Pick-up Coil Set With/Without a Core Plate

In order to verify the proposed analytic models for the self-decoupled single pick-up coil set with/without a core plate, a pick-up including only two pick-up coils A and B was assembled first, as shown in Fig. 13. The number of turns of each pick-up coil is 10, i.e., $N_o = 10$, and the size of the core plates is $l_a = 120$ cm and $l_b = 120$ cm. The shape of the coils is not a perfect rectangle, but a round-cornered rectangle due to the

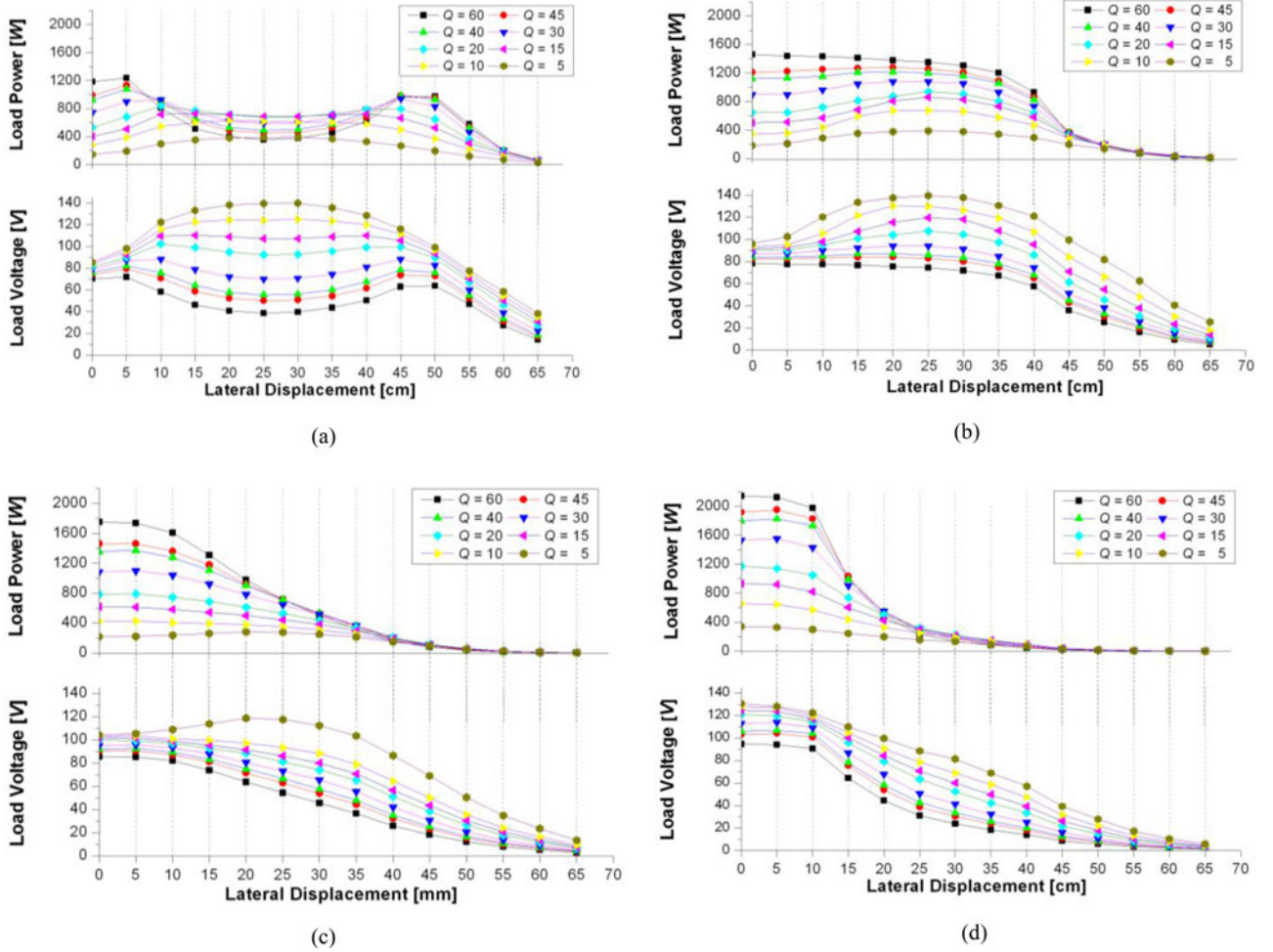


Fig. 17. Measured load power and voltage of the self-decoupled dual pick-up coil with a core plate w.r.t. x_1 . (a) $x_1 = 62$ cm. (b) $x_1 = 57.5$ cm. (c) $x_1 = 52$ cm. (d) $x_1 = 42$ cm.

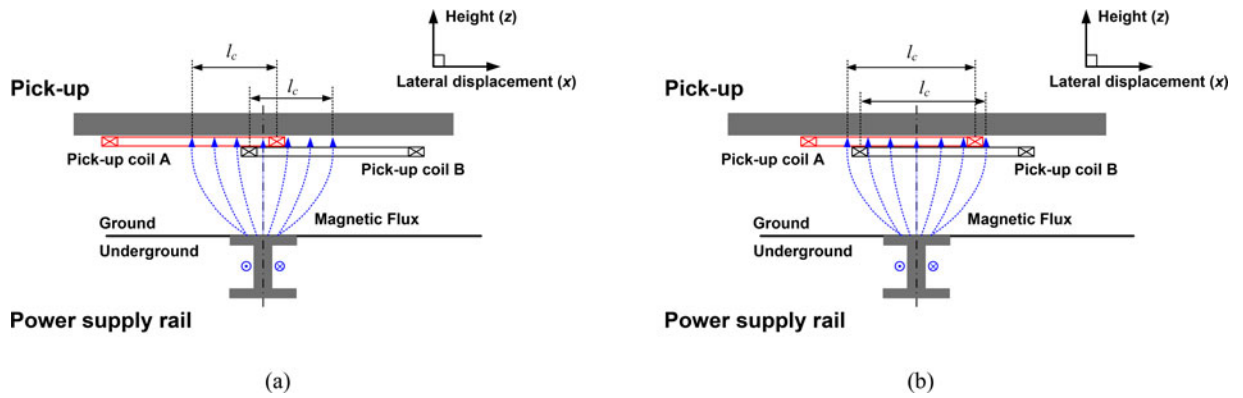


Fig. 18. Magnetic flux linkage between the power supply rail and the dual pick-up coils A-A' and B-B'. (a) Small overlapped case. (b) Large overlapped case.

difficulty in winding. The core plate is fabricated by assembling ferrite core pieces of $10 \text{ cm} \times 10 \text{ cm} \times 1 \text{ cm}$.

The mutual inductance L_m between pick-up coils A and B with/without a core plate for different x_1 was measured and compared with the calculation result, as shown in Fig. 14. As expected from the magnetic mirror model (12) and the previous

simulation results of Fig. 11, the mutual inductance with a core plate is nearly two times of that without a core plate, and the self-decoupling distance x_{opt} to meet the condition $L_m = 0$ is unchanged. Here, the x_{opt} shows a slight discrepancy between the experiment results and calculation results due to the asymmetrical and rounded shape of pick-up coils A and B.

B. Self-Decoupled Dual Pick-up Coil Set With/Without a Core Plate

A self-decoupled dual pick-up coil set with/without a core plate was also assembled for experimental verification of the design, as shown in Fig. 15. Each dual pick-up coil set includes two serially connected pick-up coils A-A' or B-B', where the number of turns of each pick-up coil is 10, i.e., $N_o = 20$ and the size of a core plate is now $l_a = 120$ cm and $l_b = 180$ cm.

The mutual inductance L_m between the dual pick-up coil set A-A' and B-B' with/without a core plate with respect to x_1 was measured and compared with the calculation result for the single pick-up coil set, as shown in Fig. 16. Note that the calculation results of (11) and (12) are valid only for the single pick-up coil set A-B, and there is no appropriate model developed for the dual pick-up case. Similar with the single pick-up coil case, the mutual inductance with a core plate is about two times that without a core plate and the optimum distance x_{opt} with/without a core plate is unchanged, as identified from Fig. 16. However, there is an appreciable difference between the measured L_m for the dual pick-up coil set and the calculated L_m for the single pick-up coil set, which stems from the cross coupling between the pick-up coils A'-B and A-B'.

The magnetic flux contribution of the coil A' to the coil B is the opposite of that of the coil A to the coil B when x_1 is large; therefore, the cross coupling increases the value of L_m , which results in the increase of x_{opt} . In this way, the self-decoupling distance x_{opt} has been increased from 52.5 to 57.5 cm for the dual pick-up coil set. This increase in the x_{opt} is beneficial to the enlargement of a lateral tolerance.

C. Load Power of the Self-Decoupled Dual Pick-up Coil Set With a Core Plate

In order to confirm the effect of a self-decoupled dual pick-up coil set with a core plate, the load power and voltage were measured along to a lateral displacement x_d with respect to x_1 and quality factor Q , as shown in Fig. 17. For simplicity, the results for only a half of the lateral displacement are shown by averaging out the left- and right-side measurements. As the overlap l_d is too small, as shown in Fig. 17(a), or it is too large, as shown in Fig. 17(c) and (d), the lateral tolerance becomes small. When it is self-decoupled, i.e., $x_1 = x_{opt} = 57.5$ cm, the lateral tolerance is as large as $l_t = 110$ cm for $Q = 5$, as identified from Fig. 17(b). This large lateral tolerance is quite close to the theoretical estimation of (1a), which is $l_t \cong 2l_w - l_d = 119.5$ cm. For a large enough load power of 1.5 kW, the load resistance should be small, i.e., the quality factor should be large $Q = 60$, as shown in Fig. 17(b). Under this condition, the lateral tolerance becomes $l_t = 90$ cm, which is about 1.5 times of a coil width $l_w = 62$ cm.

The measured load power and voltage, as shown in Fig. 17, reflect the power loss factors of internal coil resistances, core losses, and ESR's of capacitors, which could not be considered in the proposed model. The effects of these nonideal circuit parameters on the lateral displacement and power efficiency are left for further works. The peak load power is normally achieved at $x_d = 0$ and becomes high as the overlap increases,

as identified from Fig. 17. The peak load power is as much as 2.2 kW, as shown in Fig. 17(d). This is due to the increased induced voltage of V_s with a virtue of a large coupling area ($l_c \times l_l$) between the power supply rail and pick-up coils, as shown in Fig. 18. This high power, however, cannot be utilized in practice because of the evidently large penalty of the reduced lateral tolerance.

Therefore, it can be concluded that the self-decoupled dual pick-up coil set is the optimum solution that provides both a large lateral tolerance and high load power.

IV. CONCLUSION

The proposed self-decoupled dual pick-up coils and I-type power supply rail were verified to have a large lateral tolerance and high power. The proposed optimum distance between a coupled coil set was found to be so general that it is applicable to cases with/without core plate or any compensation schemes. Moreover, the proposed model is applicable to single/dual pick-ups; hence, the self-decoupled pick-up coils can be used not only for RPEV but also for stationary charging systems. Detailed analyses for the cross magnetic coupling effect and the magnetic mirror effect of a finite-size core plate are left for further work.

REFERENCES

- [1] S. W. Lee, W. Y. Lee, J. Huh, H. J. Kim, C. B. Park, G. H. Cho, and C. T. Rim, "Active EMF cancellation method for I-type pick-up of on-line electric vehicles (OLEV)," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2011, pp. 1980–1983.
- [2] S. Y. Choi, B. W. Gu, S. W. Lee, W. Y. Lee, J. Huh, and C. T. Rim, "Generalized active EMF cancel methods for wireless electric vehicles," *IEEE Trans. Power Electron.*, vol. 29, no. 11, pp. 5770–5783, Nov. 2014.
- [3] N. P. Suh, D. H. Cho, C. T. Rim, J. W. Kim, G. H. Jung, J. Huh, K. H. Lee, Y. D. Son, J. Y. Choi, E. H. Park, Y. J. Cho, J. C. Jang, Y. H. Kim, and H. G. Kim, "Collector device for electric vehicle with active cancellation of EMF," KR Patent 10-1038759, May 27, 2011.
- [4] J. G. Bolger, "Urban electric transportation systems: The role of magnetic power transfer," in *Proc. IEEE WESCON/94 Conf.*, 1994, pp. 41–45.
- [5] G. A. Covic and J. T. Boys, "Modern trends in inductive power transfer for transportation applications," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 1, no. 1, pp. 28–41, Mar. 2013.
- [6] J. Meins, "German activities on contactless inductive power transfer," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2013.
- [7] O. C. Onar, J. M. Miller, S. L. Campbell, C. Coomer, C. P. White, and L. E. Seiber, "A novel wireless power transfer for in-motion EV/PHEV charging," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2013, pp. 3073–3080.
- [8] J. M. Miller, O. C. Onar, and P. T. Jones, "ORNL developments in stationary and dynamic wireless charging," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2013.
- [9] N. P. Suh, D. H. Cho, and C. T. Rim, "Design of on-line electric vehicle (OLEV)," in *Proc. CIRP Des. Conf.*, 2010, pp. 3–8.
- [10] S. W. Lee, J. Huh, C. B. Park, N. S. Choi, G. H. Cho, and C. T. Rim, "On-line electric vehicle (OLEV) using inductive power transfer system," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2010, pp. 1598–1601.
- [11] J. Huh, S. W. Lee, C. B. Park, G. H. Cho, and C. T. Rim, "High performance inductive power transfer system with narrow rail width for on-line electric vehicles," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2010, pp. 647–651.
- [12] J. Huh, S. W. Lee, W. Y. Lee, G. H. Cho, and C. T. Rim, "Narrow-width inductive power transfer system for on-line electrical vehicles (OLEV)," *IEEE Trans. Power Electron.*, vol. 26, no. 12, pp. 3666–3679, Dec. 2011.
- [13] S. Y. Choi, J. Huh, W. Y. Lee, S. W. Lee, and C. T. Rim, "New cross-segmented power supply rails for roadway powered electric vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5832–5841, Dec. 2013.
- [14] S. Y. Choi, J. Huh, W. Y. Lee, J. G. Cho, and C. T. Rim, "Asymmetric coil sets for wireless stationary EV chargers with large lateral tolerance

- by dominant field analysis," *IEEE Trans. Power Electron.*, vol. 29, no. 12, pp. 6406–6420, Dec. 2014.
- [15] S. Y. Choi, B. W. Gu, S. Y. Jeong, and C. T. Rim "Advances in wireless power transfer systems for roadway-powered electric vehicles," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 3, no. 1, pp. 18–36, Mar. 2015.
- [16] M. Budhia, G. A. Covic, and J. T. Boys, "Design and optimization of magnetic structures for lumped inductive power transfer systems," *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3096–3108, Nov. 2011.
- [17] G. A. Covic, J. T. Boys, M. Kissin, and H. Lu, "A three-phase inductive power transfer system for roadway power vehicles," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3370–3378, Dec. 2007.
- [18] C. S. Wang, G. A. Covic, and O. H. Stielau, "Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer systems," *IEEE Trans. Ind. Electron.*, vol. 51, no. 1, pp. 148–157, Feb. 2004.
- [19] M. Budhia, J. T. Boys, G. A. Covic, and C.-Y. Huang, "Development of a single-sided flux magnetic coupler for electric vehicle IPT charging systems," *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 318–328, Jan. 2013.
- [20] M. Budhia, G. A. Covic, and J. T. Boys, "A new magnetic coupler for inductive power transfer electric vehicle charging systems," *IEEE Trans. Ind. Electron.*, pp. 2487–2492, Nov. 2010.
- [21] G. R. Nagendra, J. T. Boys, G. A. Covic, B. S. Riar, and A. Sondhi, "Design of a double coupled IPT EV highway," in *Proc. IEEE Ind. Electron. Soc. Conf.*, Nov. 2013, pp. 4606–4611.
- [22] C. T. Rim and G. H. Cho, "New approach to analysis of quantum rectifier-inverters," *IEEE Electron. Lett.*, vol. 25, no. 25, pp. 1744–1745, Dec. 1989.
- [23] C. T. Rim, "Unified general phasor transformation for AC converters," *IEEE Trans. Power Electron.*, vol. 26, no. 9, pp. 2465–2475, Sep. 2011.
- [24] J. Huh, W. Y. Lee, S. Y. Choi, G. H. Cho, and C. T. Rim, "Frequency-domain circuit model and analysis of coupled magnetic resonance systems," *J. Power Electron.*, vol. 13, no. 2, Mar. 2013.
- [25] S. W. Lee, B. Choi, and C. T. Rim, "Dynamics characterization of the inductive power transfer system for on-line electric vehicles by Laplace phasor transform," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5902–5909, Dec. 2013.
- [26] *Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (Up to 100 kHz)*, ICNIRP Guidelines, 1998.
- [27] D. Kwiat, S. Saoub, and S. Einav, "Calculation of the mutual induction between coplanar circular surface coils in magnetic resonance imaging," *IEEE Trans. Biomed. Eng.*, vol. 39, no. 5, pp. 433–436, May 1992.
- [28] G. A. Covic, M. L. G. Kissin, D. Kacprzak, N. Clausen, and H. Hao, "A bipolar primary pad topology for EV stationary charging and highway power by inductive coupling," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2011, pp. 1832–1838.
- [29] A. Zaheer, D. Kacprzak, and G. A. Covic, "A bipolar receiver pad in a lumped IPT system for electric vehicle charging applications," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2012, pp. 283–290.
- [30] W. Y. Lee, J. Huh, S. Y. Choi, X. V. Thai, J. H. Kim, E. A. Al-Ammar, M. A. El-Kady, and C. T. Rim, "Finite-width magnetic mirror models of mono and dual coils for wireless electric vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 3, pp. 1413–1428, Mar. 2013.
- [31] R. L. Steigerwald, "A comparison of half-bridge resonant converter topologies," *IEEE Trans. Power Electron.*, vol. 3, no. 2, pp. 174–182, Apr. 1988.
- [32] C. T. Rim and G. H. Cho, "Phasor transformation and its application to the dc/ac analyses of frequency phase-controlled series resonant converters (SRC)," *IEEE Trans. Power Electron.*, vol. 5, no. 2, pp. 201–211, Apr. 1990.
- [33] S. Kim, A. Zaheer, G. Covic, and J. Boys, "Tripolar pad for inductive power transfer systems," presented at the 40th Annual Conference of IEEE Industrial Electronics Society, Dallas, TX, USA, 2014.



Su Y. Choi (S'13) received the B.S. degree in mechanical engineering from Pusan National University, Pusan, Korea, in 2011, and is currently working toward the Integrated master's Ph.D. degree in nuclear and quantum engineering at the Korea Advanced Institute of Technology, Daejeon, Korea.

His current research interests include power converters, inductive power transfer system, and online electric vehicles.



Seog Y. Jeong (S'13) received the B.S. degree in electrical engineering from Kyungpook National University, Daegu, Korea, in 2013, and is currently working toward the master's degree in nuclear and quantum engineering at the Korea Advanced Institute of Science and Technology, Daejeon, Korea.

His current research interests include online electric vehicles, wireless power transfers.



Eun S. Lee (S'13) was born in Korea in 1986. He received the B.S. degree in electrical engineering from Inha University, Incheon, Korea, in 2012, and the M.S. degree in nuclear and quantum engineering from the Korea Advanced Institute of Science and Technology, Daejeon, Korea, in 2014, where he is currently working toward the Ph.D. degree.

His current research interests are in the field of power converter, LED drivers, and wireless power transfer.



Beom W. Gu (S'13) received the B.S. degree in mechanical engineering from Pusan National University, Pusan, Korea, in 2013, and is currently working toward the Integrated master's Ph.D. degree in nuclear and quantum engineering at the Korea Advanced Institute of Science and Technology, Daejeon, Korea.

His current research interests are in the field of wireless power transfer, online electric vehicle, and power converter.



Sung W. Lee (M'13) received the B.S. degree from Korea University, Seoul, Korea, in 2007, and the Ph.D. degree in electrical engineering from the Korea Advanced Institute of Science and Technology, Daejeon, Korea, in 2013.

He is currently with Samsung Electronics, Suwon, Korea. His research interests are in the field of analog integrated circuit design, and his current research areas are in the power management IC and in the contactless power supply.



Chun T. Rim (M'90–SM'11) was born in Korea, in 1963. He received the B.S. degree in electrical engineering from the Kumoh Institute of Technology, Gumi-si, Korea, in 1985, and the M.S. and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Technology (KAIST), Daejeon, Korea, in 1987 and 1990, respectively.

Since 2007, he has been an Associate Professor of nuclear and quantum engineering, and an Adjunct to aerospace engineering in power electronics at KAIST.

He is currently developing various wireless power technologies including inductive power transfer systems for online electrical vehicles and leading the Nuclear Power Electronics and Robots Lab at KAIST. From 1990 to 1995, he was a Military Officer at the Ministry of National Defense in Korea. From 1995 to 2003, he was a Senior Researcher at the Agency for Defense Development, Daejeon, and from 1997 to 1999, he was with Astrium in Portsmouth, U.K. From 2003 to 2007, he was a Senior Director at the Presidential Office, Seoul, Korea. He was involved in developing Korea's first airborne and spaceborne Synthetic Aperture Radars. He has authored or coauthored 118 technical papers, written five books, and holds more than 117 patents (awarded and pending). His research areas include wireless electric vehicles, wireless power systems for robots and biomedical applications, and general unified modeling of power electronics.

Dr. Rim won three prizes awarded by the Korean government and has been the Chair of wireless power committee of KPE since 2010 and Chair of the EV charger committee of KIEE since 2011. He is currently an Associate Editor of *IEEE TRANSACTIONS ON POWER ELECTRONICS* and the *JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS* (JESTPE), a Guest Editor of the *Special Issue on Wireless Power Transfer* of the *IEEE TRANSACTIONS ON POWER ELECTRONICS* and the JESTPE, and the General Chair of the 2014 IEEE VTC-Workshop on Wireless power (WoW) and 2015 IEEE WoW.