Quasistatic Approximation for Exposure Assessment of Wireless Power Transfer

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SUMMARY  Magnetic resonant coupling between two coils allows effective wireless transfer of power over distances in the range of tens of centimeters to a few meters. The strong resonant magnetic field also extends to the immediate surroundings of the power transfer system. When a user or bystander is exposed to this magnetic field, electric fields are induced in the body. For the purposes of human and product safety, it is necessary to evaluate whether these fields satisfy the human exposure limits specified in international guidelines and standards. This work investigates the effectiveness of the quasistatic approximation for computational modeling human exposure to the magnetic fields of wireless power transfer systems. It is shown that, when valid, this approximation can greatly reduce the computational requirements of the assessment of human exposure. Using the quasistatic modeling approach, we present an example of the assessment of human exposure to the non-uniform magnetic field of a realistic WPT system for wireless charging of an electric vehicle battery, and propose a coupling factor for practical determination of compliance with the international exposure standards.

key words: wireless power transfer, human exposure, dosimetry

1. Introduction

Wireless power transfer (WPT), which is based on magnetic resonant coupling between two coils, allows effective wireless transfer of power over distances in the range of tens of centimeters to a few meters [1], [2]. When users or bystanders are moving in the electromagnetic field produced by a WPT system, electric fields and currents are induced in the body. This raises concerns about the safety of WPT for general public use. Open questions about the exposure of humans to the fields of WPT need to be solved before the technology can be adopted widely.

Several international guidelines and standards limit the human exposure to electromagnetic fields [3]–[5]. In the guidelines developed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [3], [4], the reference levels for exposure are given in terms of the strength of the external electromagnetic fields, and the basic restrictions are defined in terms of the specific energy absorption rate (SAR) at frequencies higher than 100 kHz and the induced electric field at frequencies lower than 10 MHz. It is notable that the magnitudes of the magnetic and electric fields used in WPT especially in the 10 MHz band considerably exceed the reference levels [6], [7]. Therefore, it is necessary to investigate whether the SAR induced in the body satisfies the basic restrictions. This investigation requires the use of computational dosimetry of the electromagnetic fields in the human body.

Until now, few studies have computationally investigated human exposure to electromagnetic fields of WPT systems [6]–[9]. A feature of the frequency band of WPT is that it falls between the low- and high-frequency regimes. At high frequencies, full-wave computational methods, such as the finite-difference time-domain method [10], are used. These methods numerically solve the complete Maxwell equations, but they can be very intensive computationally, especially at lower frequencies. In contrast, at low frequencies, computationally effective methods, which are based on the quasistatic approximation, are used.

The applicability of the quasistatic approximation for dosimetry of WPT is unclear, because the fields of WPT are highly resonant and the operation frequencies are much higher than the frequencies for which the quasistatic approximation has been previously used. This study discusses the applicability of the quasistatic approximation for the evaluation of human exposure to the fields of WPT. The quasistatic approximation can lead to an extreme reduction of computational requirements compared to full wave methods, and, when valid, greatly facilitates the exposure assessment of WPT.

2. Theory

2.1 Quasistatic Approximation

Consider the scenario where a body consisting of biological tissue is exposed to an incident magnetic field \( \mathbf{B}_0 = \nabla \times \mathbf{A}_0 \) and an incident electric field \( \mathbf{E}_0 \) that are produced by a WPT system.

Under the quasistatic approximation, the electromagnetic fields are assumed to change so slowly that at each instant, the fields can be considered to be at equilibrium. In this work, the quasistatic approximation consists of the following assumptions. The first assumption is that the displacement current term in the Maxwell equations is set to be zero. The second assumption is that the secondary magnetic field induced by the currents flowing in the body, i.e., the magnetic skin effect, is ignored. This is a valid assumption.
because the conductivities of biological tissues are much smaller than those of metals and the operation frequencies are not very high. With these assumptions, the electromagnetic problem splits into two separate parts: the “magnetoquasistatic” and “electroquasistatic” problems. Note that the definitions adopted here for magneto- and electroquasistatic approximations may differ from the definitions commonly applied in other fields of physics or electromagnetics, particularly with respect to neglecting the magnetic skin effect.

For the magnetoquasistatic problem, the induced electric field is solenoidal, i.e., there is no accumulation of electrical charges, and the electric current flows in closed loops. The electric field induced by the magnetic field is \( \mathbf{E}_{\text{MQS}} = -\nabla \phi_M - \frac{\partial}{\partial t} \mathbf{A}_0 \), where \( \phi_M \) is the electric scalar potential, which satisfies the following elliptic equation:

\[
\nabla \cdot \sigma \nabla \phi_M = -\nabla \cdot \sigma \frac{\partial}{\partial t} \mathbf{A}_0
\]

with the boundary condition

\[
\mathbf{n} \cdot \mathbf{J} = \sigma \mathbf{n} \cdot \left( -\nabla \phi_M - \frac{\partial}{\partial t} \mathbf{A}_0 \right) = 0,
\]

where \( \sigma \) is the conductivity, \( \mathbf{J} \) is the current density, and \( \mathbf{n} \) is the outer normal vector of the body surface.

The electroquasistatic electric field is irrotational. Its source is a slowly pulsating surface charge distribution that is induced on the surface of the body by the external electric field. The induced electric field is \( \mathbf{E}_{\text{EQS}} = -\nabla \phi_E \), where the electric scalar potential \( \phi_E \) satisfies the homogeneous elliptic partial differential equation

\[
\nabla \cdot \sigma \nabla \phi_E = 0
\]

with the boundary condition

\[
\mathbf{n} \cdot \mathbf{J} = -\sigma \mathbf{n} \cdot \nabla \phi_E = -\frac{\partial}{\partial t} \rho_s,
\]

where \( \rho_s = \varepsilon_0 \mathbf{n} \cdot \mathbf{E}_{\text{ext}} \) is the surface charge distribution induced by the external electric field \( \mathbf{E}_{\text{ext}} \). The electroquasistatic approximation results in more complicated calculations, as determining the external electric field \( \mathbf{E}_{\text{ext}} \) from the incident electric field \( \mathbf{E}_0 \) is a separate nontrivial task that requires the use of numerical methods.

In this work, we define

\[
\mathbf{E}_{\text{FQS}} = \mathbf{E}_{\text{MQS}} + \mathbf{E}_{\text{EQS}},
\]

which is the electric field by the “full quasistatic” approximation, i.e., it includes the contribution from both incident magnetic and electric fields. Possible phase differences [1] between the magneto- and electroquasistatic electric fields were ignored in this work to consider the worst case scenario.

2.2 Full-Wave Analysis

In this work, full-wave analysis means analysis of the electric and magnetic fields using the “full” Maxwell equations, taking into account displacement current and the secondary magnetic and electric fields. Full-wave analysis also takes into account the effects of the presence of the body on the power transfer characteristics. In full-wave analysis, the magnetic and electric fields are coupled.

3. Applicability of QS Approximation

3.1 Assessment of Human Exposure

In [9], we investigated the applicability of the quasistatic approximation for SAR calculations for a WPT system that consisted of two identical perfectly electrically conducting helical coils [11]. The system operates in the 10 MHz band, which is the highest frequency band considered for magnetic-resonance WPT systems. The dimensions of the coils were the following: diameter 30 cm, width 20 cm, number of turns 5, and wire diameter 2 mm. The odd resonance mode (11.36 MHz) was considered. The transmitting coil was excited by a voltage source located at the midpoint of the wire. Our investigation was limited to only one frequency, as the geometry of the system would need to be altered for each operating frequency.

A cylindrical human phantom whose dielectric properties were equal to 2/3 of those of the muscle tissue [12] was placed next to the coils. Some of the cases that we considered are shown in Fig. 1. Due to the presence of the cylinder, the electric field is perturbed, resulting in mismatch of the impedance or lowered transfer efficiency. To correct this, for each case, the resonant frequency was kept constant at 11.36 MHz by adding a suitable capacitance to the input voltage source. This simulated a realistic power transfer system, where an active feedback circuit controls that the transfer frequency stays unchanged when humans and objects move in the vicinity of the system.

The electric field and the magnetic vector potential near the WPT system and inside the cylinder were first determined using full-wave analysis (FEKO, EMSS). The calculated magnetic vector potential was used for the magnetoquasistatic analysis. For the electroquasistatic analysis, we calculated the surface charge distribution \( \rho_s \) on the surface of the cylinder from the normal component of the external electric field by the Gauss law (while neglecting the full-wave electric field inside the cylinder). The purpose of performing the full-wave analysis in advance of the quasistatic analysis was to make sure that the field sources were identical for both approaches, which allowed direct comparison of the results. In practical simulations, one would determine the magnetic vector potential/surface charge density using methods other than full-wave analysis (because we would already know all induced quantities after the full-wave analysis has finished). For numerically solving Eqs. (1) and (3), an in-house solver that implements the scalar-potential finite-difference method [13] was used.

The specific absorption rate (SAR) was calculated from the induced electric fields by
\[ \text{SAR} = \frac{\sigma |\mathbf{E}|^2}{2 \rho}, \]  

where \( \rho = 1000 \text{kg/m}^3 \), and it was averaged over 10 g cubical volumes [14]. The SAR calculated with magnetoquasistatic approximation was compared with the SARs calculated with the full quasistatic approximation. In addition, the full quasistatic SAR was compared to the SAR determined using full wave analysis. The errors in the SAR were defined as

\[
\text{error I} = \frac{\text{SAR}_{\text{MQS}} - \text{SAR}_{\text{FQS}}}{\text{SAR}_{\text{FQS}}} \times 100\% \tag{7}
\]

\[
\text{error II} = \frac{\text{SAR}_{\text{FQS}} - \text{SAR}_{\text{FW}}}{\text{SAR}_{\text{FW}}} \times 100\%, \tag{8}
\]

where \( \text{SAR}_{\text{MQS}}, \text{SAR}_{\text{FQS}}, \text{and SAR}_{\text{FW}} \) are the peak 10 g averaged SARs calculated using magnetoquasistatic, full quasistatic and full-wave analysis, respectively. For simplicity, we only compared the peak SAR values. This comparison is valid because the locations of the peak SARs for MQS, FQS, and full wave solutions were located close to each other in each case (less than 2 cm difference).

Table 1 lists the calculated SAR in each case of Fig. 1 for the magnetoquasistatic, electroquasistatic, full quasistatic, and full-wave solutions. The separation \( D \) between the cylinder and the WPT coil was varied from 1 to 10 cm. Table 2 shows the error in the SAR of the magnetoquasistatic solution compared with the full quasistatic solution (error I). The magnitude of the error decreases when the distance \( D \) between the cylinder and the coils increases. This is due to the fact that the external electric field is more concentrated near the coils than the magnetic field. The errors are the largest in case (5). For this case, the cylinder effectively “short circuits” the two coils. In summary, it seems that it is acceptable to ignore the contribution of the electroquasistatic electric field on the SAR.

For exposure assessment, the primary advantage of this observation is that it is sufficient to determine the magnetic field distribution of the WPT system—modeling the external electric field, which can be complicated and depends on the position and shape of the body phantom, is not needed. Previously, it has been shown that the magnetic field is negligibly disturbed by the body [6], [7], [9], [15]. Therefore, the magnetic field can be first determined in free space, for instance, using method of moments, and then the same field can be used for magnetoquasistatic SAR calculations. There is no need to recalculate the magnetic field if the position or the shape of the body phantom changes. It should be noted that the error of the quasistatic approach decreases as the frequency is reduced. Therefore the quasistatic approach is applicable at least up to the 10 MHz band studied herein.

Table 2 also shows the comparison between the SAR calculated using the full quasistatic approximation and full wave analysis (error II). The difference between the two SARs is typically in the range \(-10\ldots + 10\%\), and no clear pattern can be observed. These relatively “random” differences are likely due to different computational methods that were used: the finite-element method with tetrahedral elements was used for full-wave analysis, but quasistatic calculations used the scalar-potential finite-difference method.

### Table 1

<table>
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<tr>
<th>Case (1)</th>
<th>Distance (cm)</th>
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<tr>
<td>Approach</td>
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<tr>
<td>Electroquasistatic</td>
<td>1.17 0.19 0.05 0.06</td>
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<td>Magnetostatic</td>
<td>7.31 3.55 1.93 0.60</td>
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<td>8.77 3.84 2.02 0.60</td>
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<td>Full-wave</td>
<td>9.95 3.86 1.94 0.60</td>
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<th>Distance (cm)</th>
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<tr>
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<td>7.01 4.17 2.64 0.97</td>
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<td>Full-wave</td>
<td>7.89 4.60 2.80 1.09</td>
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<tr>
<td>Full-wave</td>
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### 3.2 Power Transfer for Medical Implants

The fact that the magnetic field is not perturbed by the presence of the body enables another application for WPT: transferring power from outside to inside the body for charging of batteries of medical implants. The effects of biological tissue on the self and mutual lumped inductances of magnetically coupled coils were analyzed in [16]. One of the investigated scenarios is shown in Fig. 2. The analysis was performed numerically using the full-wave finite-element method.
that the magnetic field penetrates unobstructed into biologically tissues which further supports the validity of the quasistatic approximation.

4. Applications in Exposure Assessment

It was shown that the fields of WPT systems are magnetooquasistatic in nature. This means that the external magnetic field is the dominant source of the electric fields induced in the body. Therefore, for human exposure assessment, it is sufficient to determine the magnetic field of the WPT system in free space, and then use this magnetic field for magnetooquasistatic analysis of the induced electric field and/or SAR.

This allows very effective exposure assessment of real WPT systems, whose magnetic fields may be very inhomogeneous, and the induced electric fields strongly depend on the position and posture of the body. Therefore, finding the case which produces the worst-case exposure requires one to consider many different scenarios, which would be extremely time-consuming using full-wave techniques. However, with the magnetooquasistatic approximation, the in-

<table>
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<th>Case</th>
<th>transmitting coil</th>
<th>Receiving coil</th>
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<td>55.9</td>
<td>7.9</td>
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<tr>
<td>10 kHz</td>
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<td>7.9</td>
</tr>
<tr>
<td>100 kHz</td>
<td>55.8</td>
<td>7.9</td>
</tr>
<tr>
<td>1 MHz</td>
<td>55.8</td>
<td>7.9 – 0.2i</td>
</tr>
<tr>
<td>10 MHz</td>
<td>55.8</td>
<td>7.9 – 0.5i</td>
</tr>
<tr>
<td>100 MHz</td>
<td>55.7</td>
<td>8.1 – 2.1i</td>
</tr>
</tbody>
</table>

Table 3 The frequency dependency of the self and mutual lumped complex inductances of the transmitting and receiving coils in the scenario shown in Fig. 2. The real resistance and inductance can be obtained from the complex inductance $L'$ as $R = -\omega m[L'(\omega)]$ and $L = \text{Re}[L'(\omega)]$.
duced electric fields can be obtained effectively using a two-step approach: first, the external magnetic field is determined (only once for each WPT configuration), and second, the induced electric fields in the body are calculated using quasistatic computational techniques. This approach is further advantageous because there are very efficient numerical techniques for the second step [17].

4.1 Wireless Charging of Electric Vehicle Battery

As an example, we consider a WPT system for charging of an electric vehicle battery. The operating frequency of the system is 85 kHz, which is well within the quasistatic regime. The transferred power is 7 kW, which is considerably higher than in other proposed applications of WPT, or in other wireless technologies in this frequency range. Therefore, the example presented here is the important limiting case with a high transfer power. The analysis has been previously reported in detail in [18]. The transmitting and receiving coils are identical with a separation of 150 mm, consisting of a rectangular magnetic core with dimensions 325 mm × 405 mm and 14 turns of ideally conducting wire. The magnetic fields around a 3-D model of the vehicle were modeled using HFSS (Ansys, Inc). Figure 3 shows the magnetic field distribution near the rear of the vehicle, where the transmitting and receiving coils are located under the vehicle. It is notable that the magnetic field strength exceeds the ICNIRP reference level of 21 A/m for general public exposure to electromagnetic fields [4].

As seen in Fig. 3, the magnetic field is inhomogeneous and its direction is a complicated function of position in three dimensions. For finding the worst case exposure condition and investigating the relationship between the external magnetic field and induced electric fields, the two-step approach was utilized to calculate the induced electric fields at three different body positions, with eight body orientations at each position (Fig. 4). In addition, two different coil configurations were considered by changing the position of the receiving coil relative to the transmitting coil; each configuration produced a slightly different magnetic field distribution (not shown).

Simulations for each position were performed using three numerical anatomical human body models, which were NORMAN [19] (adult male, height 176 cm, weight 73 kg), TARO [20] (adult male, 173 cm, 65 kg), and Thelonious [21] (6-year old male, 117 cm, 20 kg), shown in Fig. 5. Each model consists of a three-dimensional segmented representation of several tissues/organisms and body fluids. The electrical properties of each tissue/body fluid were modeled using the fourth order Cole–Cole model of [12]. The resolution of the models was 2 mm × 2 mm × 2 mm, the adult models consisting of 8–9 million cubical voxels.

The total number of cases studied was 144 (two different coil configurations, three human body models, three body positions, and eight body orientations). Because there was no need to recalculate the magnetic field for each body position, each case took less than one minute to solve on a workstation with an Intel Xeon X5690 CPU using the in-house finite-element method solver that utilizes the geometric multigrid method with successive over-relaxation [17].

Because the frequency was lower than 100 kHz, the exposure was measured in terms of the 99th percentile induced electric field (maximum over each specific tissue) as recommended by the ICNIRP [4]. The induced electric fields in all studied cases are shown in Fig. 6. It can be seen that the induced electric field never exceeded the ICNIRP basic restriction of 11.5 V/m. The figure also shows a strong correlation (R² > 0.74) between the induced electric field and the average magnetic field over the whole body. The induction factor that relates the induced electric fields and the average external magnetic field was 0.12 V/m per 1 A/m in adults, while the worst-case induction factor was 0.18 V/m per 1 A/m. These results indicate that the ICNIRP basic restriction could be exceeded for average magnetic fields higher than 64 A/m, which is three times the corresponding ICNIRP reference level. This difference is due to the fact...
Linear regression lines, with regression coefficient of the magnetic field over the whole volume occupied by the body. Average magnetic field is the arithmetic average of the absolute value of the magnetic field over the whole volume occupied by the body. Each marker presents the simulation results for one body position and body model. Linear regression lines, with regression coefficient $C$ and residual $R^2$, have been fitted to the data for each anatomical body model.

that the reference levels, meant to be used for practical compliance testing, are defined for uniform exposure, and are thus not directly applicable for nonuniform exposure [4].

As shown in the above example, the magnetoquasistatic approximation together with fast computational methods allow detailed and effective exposure assessment of real-world WPT systems. Because of the inhomogeneity of realistic WPT magnetic fields, it is difficult to estimate the exposure simply by using the reference levels of international guidelines. Hence, a large number of different scenarios need to be considered for establishing compliance with the basic restrictions of human exposure. Our group and others have already successfully applied the quasistatic two-step or similar methods for various kinds of WPT systems [6], [7], [18], [22].

4.2 Coupling Factors for Product Safety Compliance

Another advantage of quasi-static approximation is that the compliance procedure of low-frequency electromagnetic fields can be applied, which only requires measuring the external magnetic field and is less complicated than that used in the high-frequency regime. For practical compliance assessment of non-uniform exposure at low frequencies, the International Electrotechnical Commission (IEC) introduced a compensation scheme for measured external magnetic field strength in terms of a coupling factor [23], [24]. Coupling factors may differ for various kinds of WPT systems. The coupling factor has been previously derived for one type of WPT system in [25].

The coupling factor (unitless) is defined by the following equation:

$$a_c = \frac{H_{\text{max}}}{H_{\text{lim}}/E_{\text{lim}}} \quad (9)$$

where $H_{\text{max}}$ is the spatial maximum value of the magnetic field strength that should be measured at the distance of 20 cm from the vehicle (or appliance), and $H_{\text{lim}}$ is the reference level of the external magnetic field defined in the ICNIRP guidelines [3], [4]. $E_{\text{max}}$ and $E_{\text{lim}}$ are the maximum value of the induced electric field and the basic restriction of the induced electric field, respectively.

The coupling factor can be determined computationally utilizing the quasistatic two-step procedure. After the coupling factor is known for a particular type of WPT system, practical compliance can be established by measuring the magnetic field at the designated location, and multiplying the measured value with the compliance factor. The product should be compared with the ICNIRP reference level.

In the case of the WPT system for the electric vehicle presented above (Sec. 4.1), the computed coupling factor is in the range between 0.035 and 0.054, suggesting that the compliance with the reference level is 18 to 29 times more conservative than that with the basic restriction.

5. Discussion

The effectiveness of the quasistatic approximation for human exposure assessment was investigated using a cylindrical human phantom placed near a WPT system operating at 11.36 MHz. Comparison with the full wave analysis showed that the quasistatic approximation leads to an error of about ±10% in the SAR. It was also shown that the SAR is primarily induced by the incident magnetic field. The SAR due to the external electric field of the WPT system is much smaller and can be ignored.

The magnetic field distribution around the coupled coils stays almost unaltered independent of the position of the body with respect to the coils [6], [7], [9]. The requirement for the above is that the shift in the resonant frequency/impedance mismatch for each body position is corrected by adjusting the input capacitance appropriately. Then the magnetic field distributions for the original (free space) and adjusted resonance modes are almost identical. This is likely to be true for any realistic WPT system. Therefore, for human exposure assessment, it is sufficient to determine magnetic field of the WPT system in free space, and then use this magnetic field for magnetoquasistatic analysis of the induced electric field.

The observation that the external electric field can be ignored seems to conflict with some recent studies [8], [26]. Namely, for the exposure to uniform magnetic and electric fields, analytic calculations show that the effect of the incident electric field cannot be ignored [26]. However, in this study, the sources of the field are located close to the body, not at an infinite distance. Therefore, the presence of the body alters not only the external electric field but also the sources of the field. After the resonant frequency is tuned so that it stays constant by a feedback circuit, the resulting magnetic field remains almost unchanged from the case of free space. However, the external electric field is altered in a way that reduces its impact on the electric field induced inside the body. Consequently, the external magnetic field dominates over the external electric field.
As discussed above, the magnetic field is not perturbed by humans or objects placed near the system. Considering a WPT system operating at 85 kHz, we showed that there is a strong correlation between the incident magnetic field and the electric fields induced in the body (Fig. 6, cf. [18]). Therefore, it is possible to estimate the induced electric fields using an induction factor that relates the external magnetic field to the internal electric field. For practical exposure assessment of WPT, it is thus sufficient to measure the external magnetic field, after which the induced electric field can be estimated. Another consequence of the validity of the quasistatic approximation is that embedding one of the coils in biological tissue does not degrade the magnetic coupling performance, which shows that the technology is applicable for use for implanted or on-body devices.

6. Summary

The magnetic fields of realistic WPT systems are often strong and inhomogeneous. Therefore, worst-case exposure assessment of WPT requires that the induced electric fields or SAR are determined for a large number of different scenarios, including different body positions, postures, and anatomical body models. The magnetoquasistatic approximation makes it possible to effectively consider such a large number of cases. With this approximation, the process of computational exposure assessment essentially consists of two steps: first, determining the external magnetic field once, and then using the same magnetic field to determine the quasistatic induced electric field in the body for various potential scenarios. We demonstrated the use of the quasistatic approach for investigating the exposure to the magnetic field of wireless electric vehicle charging system. The technique allowed determination of induction or coupling factors that relate the induced quantities with the external magnetic fields, and enable practical compliance assessment based on magnetic field measurements.

Acknowledgment

This work was supported in part by JSPS Grant-in-Aid for Scientific Research (C) 25420251.

References

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