Model for Calculation of Limits of Radio Disturbance from Wireless Power Transfer System for Electric Vehicles

-Calculation of probability factor for location coincidence-

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***Abstract*— To calculate the probability factor for location coincidence, which is one of the factors used in calculating the limit for protecting a wireless system from electromagnetic disturbance, we first propose average distance calculation models between a disturbance source and a victim receiver. Next, the propagation characteristic of the electromagnetic field from WPT system for EV on the natural ground plane is calculated by the moment method to obtain the propagation coefficient at 150 kHz–30 MHz and 1–100 m. Finally, from these results, the probability factor for location coincidence of the WPT system and some communication systems are estimated.**

Keywords*— *WPT; EV; emission; limit; CISPR16-4-4; probability factor; location coincidence

I. Introduction

In recent years, the need to introduce a wireless power transfer (WPT) system for electric vehicles (EVs) and household electrical appliances has been increasing. Along with this, there is concern about interference to telecommunication and broadcasting services due to electromagnetic disturbance emitted from the WPT system. For this reason, various international standardization bodies such as the International Committee on Radio Interference (CISPR) and others are developing the emission limit (150 kHz–30 MHz) and measurement method of WPT systems [1].

To protect radio reception from electromagnetic disturbance and prevent interference, it is necessary to reduce the disturbance level to less than the limit value, which is basically obtained by subtracting the protection ratio from the received power of the desired wave (both expressed in dB). This condition shall be satisfied at the protection distance (the distance from the disturbance source to the receiver to be protected; normally, 10 m is assumed in the CISPR standard). The value defined by the procedures above gives the limit under the worst-case condition.

In general, however, it is necessary to consider that interference does not necessarily occur even when the disturbance exceeding the limit is measured at a test site. For the generation of interference, the time, location, and frequency of both the desired wave and the disturbance must be matched (=coincident) at the victim receiver. Moreover, other probability factors such as the radiation directivities of the disturbance source and the receiving antenna also play an important role. Therefore, the statistical treatment of these factors is required to derive the acceptable limit.

For this reason, CISPR published a technical report, CISPR TR 16-4-4 [2], in which a limit-setting model based on statistical treatment is introduced. In this model, the limit is increased from the worst-case condition by the factor that are derived using the mean value and the standard deviation of each probability factor with a certain reliability.

However, CISPR TR 16-4-4 does not mention a specific calculation method of the statistical parameters (mean value and standard deviation) of the probability factor. Therefore, in this paper, the probability factor for location coincidence is mainly discussed. This factor is a statistical representation of the propagation attenuation between the protection distance (= measured distance) and the average actual distance.

We firstly propose calculation models of average actual distance using the average residential area where the disturbance source exists and the penetration rate of the victim receiver assumed that the victim receiver is uniformly distributed. In the CISPR TR 16-4-4, the propagation model (3–30 m) between the two loop antennas on the metal ground plane is described only in the appendix. The model depends on the radiation characteristics of the disturbance source and real ground condition. Therefore, the actual WPT system for EVs is modeled, and the propagation characteristics (1–100 m) on the natural ground are calculated by the moment method to estimate the propagation coefficient at 150 kHz–30 MHz.

II. Probability Factor - Location Coincidence-

The location coincidence factor gives a correction on the limit based on the difference between the measurement distance d (limit is specified at this distance, usually 10 m) and the actual/estimated distance r between the disturbance source and the victim receiver, which are statistically distributed.

According to the CISPR TR 16-4-4 (Ed.2.1)[2], its mean value μP_8 is given by equation (1) as follows:

$$\mu P_8 = x \cdot 20 \log (r/d), \quad (1)$$

where
r is the actual distance between the source and the victim;
d is the measurement distance;
x is the wave propagation coefficient.

The estimated distance has to take into account the average distance for the intended use of the radio equipment.

III. AVERAGE DISTANCE BETWEEN DISTURBANCE SOURCE AND UNIFORMLY DISTRIBUTED VICTIM RECEIVER

A. Macroscopic Model

This model is applicable to the case that the penetration rate of the victim receiver is low (e.g., LF&HF receiver, amateur radio). Suppose that the average dwelling area is S_0 and the penetration rate of the victim receiver is p. For the sake of simplicity, it is assumed that the dwelling area is circular and a disturbance source exists at the center as shown in Fig. 1. Note that the penetration rate of the disturbance source is considerably smaller than that of the victim receiver.

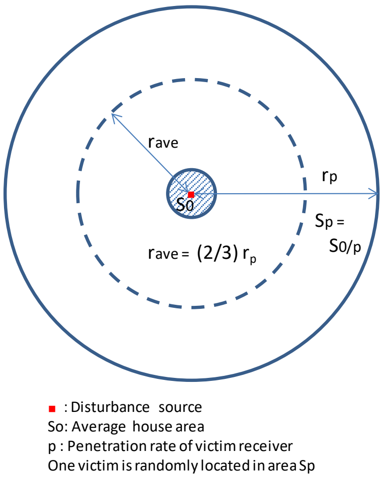


Fig. 1 Dwelling model to estimate the average distance between victim receivers and a disturbance source when penetration of victim receiver is low.

In this case, there will be one victim receiver located in the area S_p (= S_0/p). Note that the area of S_0 is derived using the average dwelling area only and there are no public spaces included such as main roads, railways, stations, parks, etc. Accordingly, the distance may be underestimated.

Assuming that the existence probability of the victim receiver is random (uniform distribution) within this circular area S_p (m^2), the average distance r_{ave} (m) and the standard deviation r_{std} (m) are calculated as

$$\begin{cases} r_{ave} = \int_0^{r_p} r \cdot pdf(r)dr = \int_0^{r_p} \frac{2r^2}{r_p^2}\, dr = \frac{2r_p}{3} = \frac{2}{3}\sqrt{\frac{S_0}{\pi p}} \\ r_{std}{}^2 = \int_0^{r_p} (r - r_p)^2 \cdot pdf(r)dr = \frac{r_p{}^2}{18}, \end{cases} \quad (2)$$

where $pdf(r) = \frac{2r}{r_p{}^2}$ is the probability density function of the receiver located at distance r.

B. Microscopic Model

This model is applicable to the case that the penetration rate of the victim receiver is very high. It is assumed that the victim receiver is located in all houses (e.g., MF Radio Receiver).

At least one side of the dwelling needs to be facing the public road and the width is w (m). Eight neighbors are arranged closest to the periphery of the dwelling in which a disturbance source is located, as shown in Fig. 2.

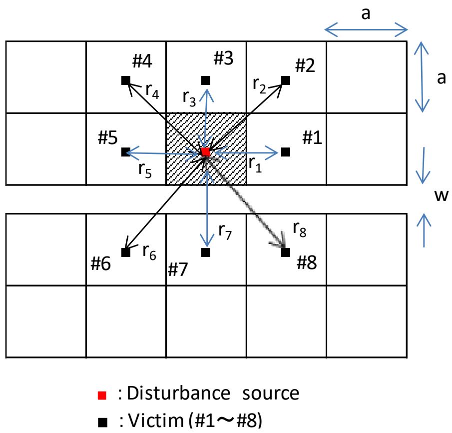


Fig. 2 Dwelling model to estimate the average distance between victim receivers and a disturbance source when penetration of victim receiver is high.

Here, for the sake of simplicity, it is assumed that the main disturbance is emitted from a point source, and the locations of the disturbance source and the victim receiver are in the center of each dwelling on average. In this case, the distances to the eight victim receivers from the disturbance source, r_j (j = 1, 2, 3 ... 8), are as follows.

$$\begin{cases} r_1 = r_3 = r_5 = a \\ r_2 = r_4 = \sqrt{2}\, a \\ r_6 = r_8 = \sqrt{a^2 + (a+w)^2} \\ r_7 = a + w. \end{cases} \quad (3)$$

Therefore, the average distance r_{ave} and the standard deviation r_{std} can be calculated as

$$\begin{cases} r_{ave} = (\sum_{j=1}^{8} r_j)/8 = \{4a + w + 2\sqrt{2}\,a + 2\sqrt{a^2 + (a+w)^2}\}/8 \\ r_{std}{}^2 = (\sum_{j=1}^{8} (r_j - r_{ave})^2)/8 \end{cases} \quad (4)$$

C. Examples

1) Average site area per dwelling

The average site area per dwelling in which the target disturbance source (WPT in this case) is installed is estimated by using available statistical data. For example, according to the official data in Japan [3], the average site area per dwelling is about 279 m^2, which is directly used in a macroscopic model.

However, this area 279 m^2 seems to be relatively large in view of the actual situation in urban/metropolitan areas in Japan. Thus, we take the median value of the section with the highest rate (100 to 199 m^2) of the above data, that is, 150 m^2, as the typical site area per dwelling in urban/metropolitan areas, which is used in a microscopic model.

2) LF and HF receivers (p = 0.01) [4]

By using the macroscopic model and S_p = 279 (m^2), we obtain

r_{ave} = 63 (m) and r_{std} = 22 (m).

3) MF Radio Receiver ($p \approx 1$)

From the consideration in *1)*, we use 150 m^2 as the typical site area per dwelling in an urban area. For simplicity, assuming that the site is a square, the length of one side a (m) is 12.4 (m). By using the microscopic model and w = 5 m is assumed, we obtain

r_{ave} = 16.6 (m) and r_{std} =3.5 (m).

IV. PROPAGATION COEFFICIENT FOR EV-WPT

A. Model for EV-WPT

As shown in Fig. 3, simulations were performed assuming the WPT system for EV(EV-WPT), which has already been analyzed in detail for a fundamental wave (85 kHz) in reference [5]. However, the analysis frequency band in this paper is from 150 kHz to 30 MHz, and the ground is assumed to be the natural ground to model the usual housing environment.

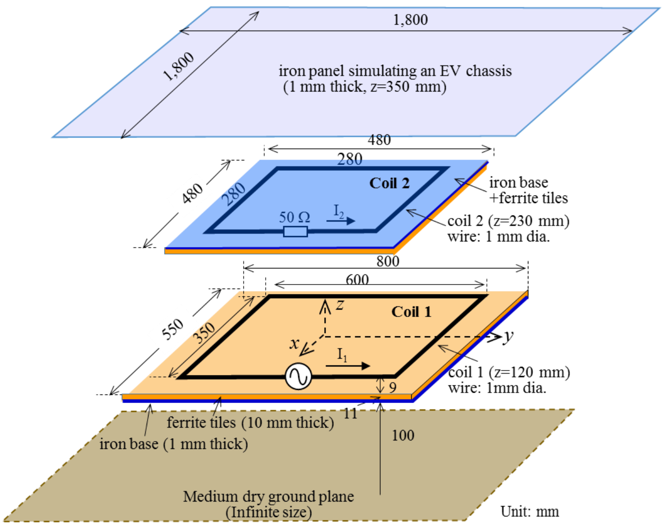


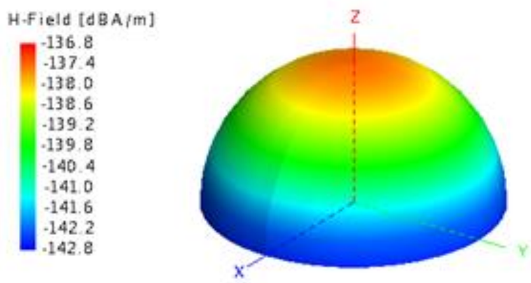
Fig. 3 Simulation model of a WPT system for EV.[5]

The electrical constant of the ground was set to be medium dry ground (ε_r = 15, $\sigma = 10^{-3}$ S/m) through the frequency band 150 kHz–30 MHz according to the model of ITU-R[6].

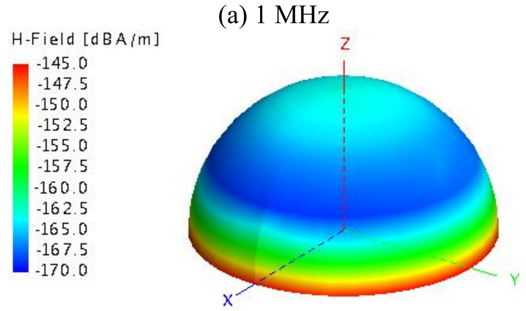
In addition, an iron panel simulating a EV chassis was placed 0.1 m above the iron substrate of the receiving coil Coil-2 (z = 0.35 m) and its size was 1.8 × 1.8 m^2. For the electromagnetic field analysis, software FEKO (MoM solver) was used.

B. Propagation Coefficient

Typical examples of the spherical pattern at a distance of 10 m are shown in Fig. 4. The directivity of the vertical plane varies depending on the frequency. At (a) 1 MHz, the magnetic field in the zenith direction is higher than that in the horizontal direction by about 6 dB. On the other hand, the horizontal direction shows the maximum level at (b) 10 MHz. The level of the zenith direction is reduced by about 20 dB. The boundary of the change in the vertical plane pattern is about 2 MHz. However, it was found that the directivity of the horizontal plane can be omnidirectional over all the target frequencies.



(a) 1 MHz

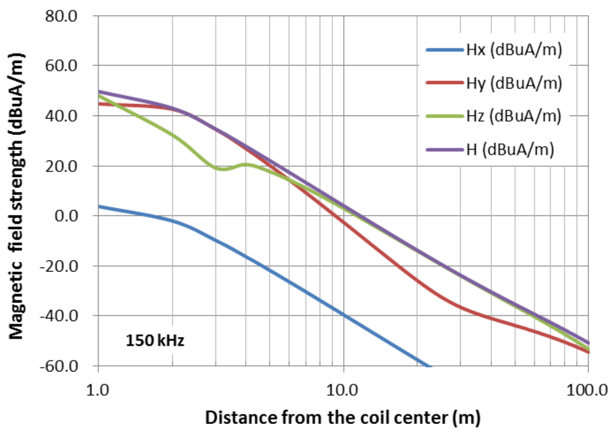


(b) 10 MHz

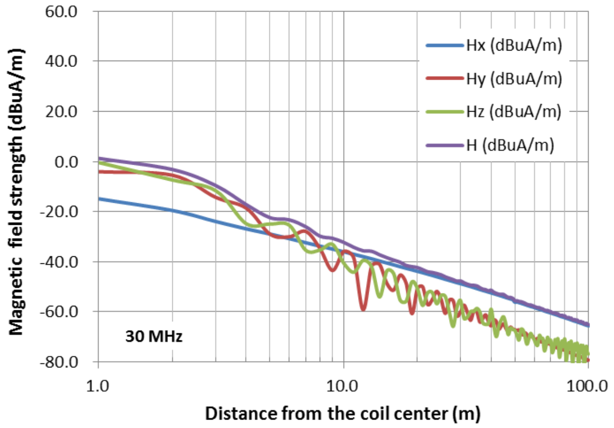
Fig. 4 Spherical pattern of total magnetic field (z = 1.3 m).

Fig. 5 shows examples of the attenuation characteristics of the magnetic field at a height of 1.3 m on the Y axis at frequencies of (a) 150 kHz and (b) 30 MHz.

Fig. 6 shows the result of the propagation coefficient x (f) in equation (1) from the level difference of the total magnetic field strength H at 10 and 100 m. Red marks indicate the simulation results and the blue line shows the proposed model in 150 kHz–30 MHz. The equation is also expressed in the second row of Table 1.



(a) 150 kHz



(b) 30 MHz

Fig. 5 Attenuation of magnetic field (z=1.3 m).

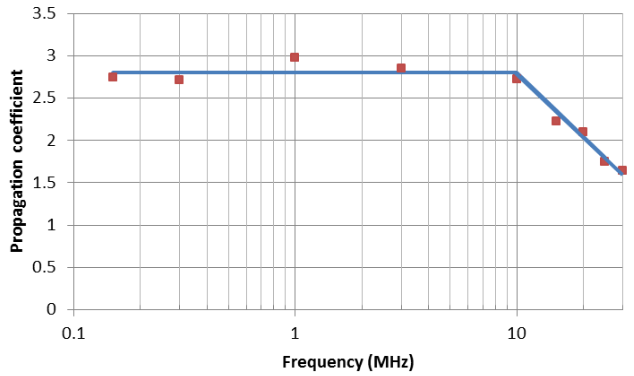


Fig. 6 Propagation coefficient in 10–100 m range (red marks, simulation; blue line, proposed model).

V. Calculation Example of Probability Factor for Location Coincidence of WPT for EV

A. LF and HF receivers

As shown in Table 1, the average value (μ_{p8}) and standard deviation (σ_{p8}) of the location coincidence range from 45–26 and 10–5 dB, respectively, depending on the frequency.

Table 1 Propagation coefficient x(f) and the location coincidence for LF & MF receivers

Frequency f (MHz)	0.15 – 10	10 - 30
propagation coefficient x (f)	2.8	2.8 decreasing linearly with log(f) to 1.6 x(f) = 1.6-2.5 log (f/30)
μ_{P8} (dB) for r(m)	56 log (r/10)	x(f) 20 log (r/10)
A: μ_{P8} for $r_{ave} - r_{std}$ = 41 (m)	34 (dB)	34 – 20 (dB)
B: μ_{P8} for r_{ave} = 63 (m)	45 (dB)	45 – 26 (dB)
C: μ_{P8} for $r_{ave} + r_{std}$ = 85 (m)	54 (dB)	54 – 30 (dB)
μ_{P8} (= B) (dB)	45 (dB)	45 – 26 (dB) μ_{P8}(f) = 26 – 39.8 log (f/30)
σ_{P8} (= (C-A) / 2) (dB)	10 (dB)	10 – 5 (dB) σ_{P8}(f) = 5 – 10.5 log (f/30)

B. MF Radio Receiver ($p \approx 1$)

The propagation coefficient for the MF radio is 2.8 since its frequency range is about 0.5–1.6 MHz. By using the distance parameters shown in III-C-3), we calculated μ_{p8} and σ_{p8} as 12.3 and 5.3 dB, respectively.

VI. Conclusion

To calculate the probability factor for location coincidence, which is one of the factors used in calculating the limit for protecting a wireless system from electromagnetic disturbance, we first proposed average distance calculation models between a disturbance source and a victim receiver, which is uniformly distributed. Next, the propagation characteristics of the electromagnetic field from WPT system for EV on the natural ground plane were analyzed by the moment method to obtain the propagation coefficient for 150 kHz–30 MHz and 1–100 m. Finally, from these results, statistical data for the location coincidence of WPT system for EV and some communication systems were estimated.

Acknowledgment

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