The EMI Characteristics of the Electric Field Resonance Type Wireless Power Transfer System

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ABSTRACT The Wireless Power Transfer (WPT) has been drawing the attention as a technology for charging an electric vehicle and a mobile equipment in a non-contact manner. Since the WPT system utilizes the high-frequency power, there is a concern related to the interference to the broadcasting and the wireless communication due to the unnecessary radiated emission, etc. Therefore, except for some systems, it is necessary to satisfy the Electro-Magnetic Interference (EMI) allowable value of the high frequency utilization equipment in accordance with the Article 65 of the Radio Equipment Regulation and to obtain the installation permit. We have developed the electric field resonance type WPT system with a frequency of 13.56 MHz and an output power of 1 kW that satisfies the EMI allowable value specified for the high frequency utilization equipment and have obtained the installation permit.
In this paper we will report the various characteristics of this system.

1. INTRODUCTION

The research on the WPT has been actively conducted as a technology for charging an electric vehicle and a mobile equipment in a non-contact manner without connecting a power cable. Particularly, since the electrification of the automobile is progressing with the background of the global energy problem, the expectation of the WPT to the electric vehicles is also growing. In Japan, the institutionalization of the WPT for the electric vehicle has been promoted ahead of the rest of the world and the development has been very active.

In this paper, we will explain the status of the institutionalization and the standardization of the WPT system, especially for the Radio Law high frequency utilization equipment in Japan and also will report the characteristics of the developed electric field resonance type WPT system, the EMI measurement result, etc.

2. ABOUT THE INSTITUTIONIZATION AND THE STANDARDIZATION OF THE WPT

2.1 The Status of the Standardization of the EMC Regulation

The WPT system has been discussed also at CISPR (an International Radio Interference Special Committee; an organization that works for the international standardization of the specifications in area such as the Electro-Magnetic Compatibility (EMC) measurement method and the allowable value of the wireless equipment.). In CISPR, the WPT system is regarded as the Industrial, Scientific and Medical (ISM) equipment and the revision of the international standard CISPR 11 that defines the EMI measurement method of the ISM equipment and the allowable value is under way.

2.2 The Status of the Institutionalization in Japan

2.2.1 The legal position of the WPT system

In Japan, based on the Article 100 of the Radio Law, the equipment corresponding to the following is deemed to be a high frequency utilization equipment and it is stipulated to obtain the permit from the Ministry of Internal Affairs and Communications Minister before installing the equipment.

1) The telegraph, the telephone and the other communication equipment that passes a high frequency current of 10 kHz or more to the electric line.
2) The industrial heating equipment, the medical equipment and the various equipment utilizing a high frequency current of 10 kHz or more (the equipment other than the communication).

In these equipment, an unnecessary radiated emission and a conducted noise occur due to the use of a high frequency current and may interfere with the broadcasting and the wireless communication so that the installation permit is required. The WPT system is no exception and the WPT system using a radio wave of 50 W or more (10 kHz or more and less than 3 THz) requires the permit to install the high frequency utilization equipment in accordance with the Article 45 of the Radio Law Enforcement Regulation. The WPT system for the mobile equipment,

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etc. is also regarded as a high frequency utilization equipment, but the installation permit is not required if the transmission power is 50 W or less.

In Japan, the institutionalization of the WPT is being advanced ahead of the rest of the world. The Ministry of Internal Affairs and Communications Ordinance No. 15 dated March 15, 2016 was promulgated and enforced and the ministerial ordinance revision of the Article 45, 46 of the Enforcement Regulation of the Radio Law, etc. was made. The following WPT equipment for the general purpose and the non-contact power transfer equipment for the electric vehicle are newly added as the equipment that can designate the type of the high frequency utilization equipment.

- "400 kHz band electric field coupling type non-contact power transfer equipment for the general purpose"
- "6.7 MHz band magnetic field coupling type non-contact power transfer equipment for the general purpose"
- "non-contact power transfer equipment for the electric vehicle"

However, in order to receive these type designations, in accordance with the Ministry of Internal Affairs and Communications Public Notice No. 69 to 71 in 2016, it is necessary to adapt to the criteria for the measurement method of the conducted noise emission and the unnecessary radiated emission, the safety equipment for the radio wave intensity, etc. Figure 1 shows the legal position of these WPT systems. If these type designations can be received, the individual application for the installation will be unnecessary so that it is expected to be widely sold, utilized and popularized. In the future, it is thought that the institutionalization will also expand for the WPT systems applied to the industrial equipment such as a rapid charging, a large power for the electric buses, an Automated Guided Vehicle (AGV) and etc.

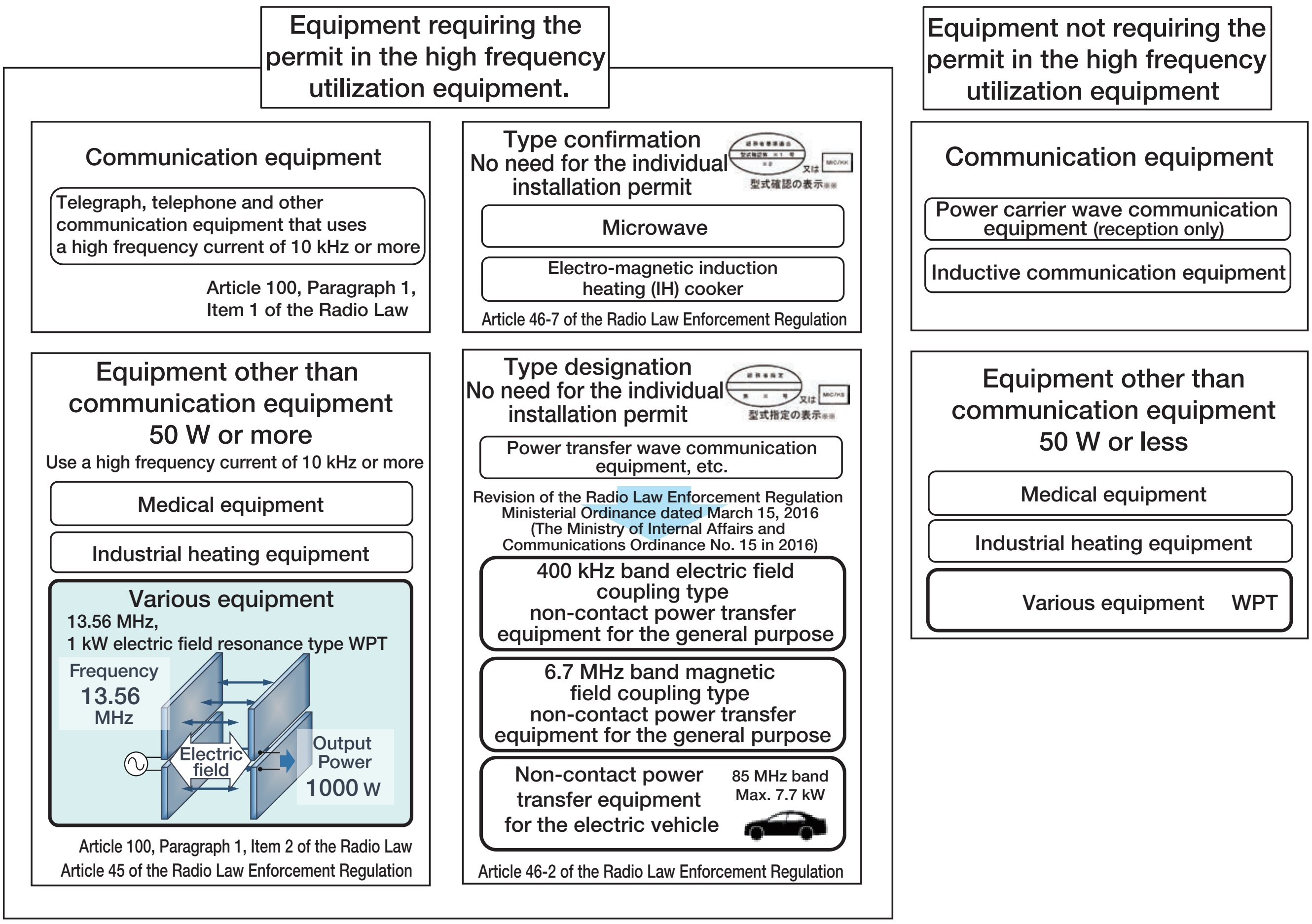

Figure 1 The legal position of the WPT system.

3. THE DEVELOPMENT OF THE ELECTRIC FIELD RESONANCE TYPE COUPLER

3.1 The Features of the Electric Field Coupling Type WPT

For the coupler structure of the electric field coupling type WPT, a meander line shape[1)], a flat plate electrode plate shape[2)] and etc. are studied. Since a meander line shape utilizes the resonance due to the inductance and the capacitance of the pattern itself, it is unnecessary to add an inductance and a planar structure can be taken. However, due to the length of the transmission line and the pattern structure, the loss in the high frequency band increases under the influence of the skin effect and the proximity effect when the high frequency current.is flowing. On the other hand, when a flat plate electrode is used, it is necessary to add an inductance such as a resonance coil, etc., but a pattern like the meander line is unnecessary and the loss in the high frequency band can be reduced.

In addition, in the electric field coupling type WPT, which positively utilizes the resonance, a high voltage is generated using the resonance and conversely the current can be reduced. As a result, the electrode material can be constructed using an inexpensive metal material such as aluminum, iron, etc. having a lower electrical conductivity than copper.

3.2 About the Electric Field Resonance Type Coupler[3), 4)]

3.2.1 The structure of the electric field resonance type coupler

We are developing the electric field resonance type coupler using a flat plate electrode and a resonance coil. The coupler has a series resonance structure in which a plate electrode and a resonance coil are connected in series. Each of the power transmission side coupler and the power reception side coupler is designed to resonate at a specific frequency by itself. This coupler is named as the electric field resonance type coupler because the couplers having the same resonance frequency are used in pairs. Figure 2 and Figure 3 show a schematic view and an equivalent circuit diagram of the coupler. The structure of the coupler itself is a very simple structure.

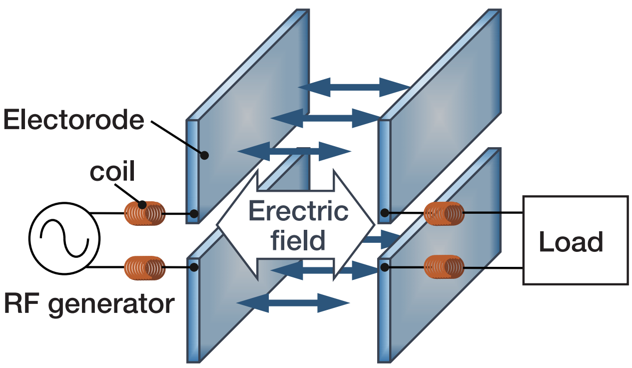

Figure 2 The schematic view of the electric field resonance type coupler.

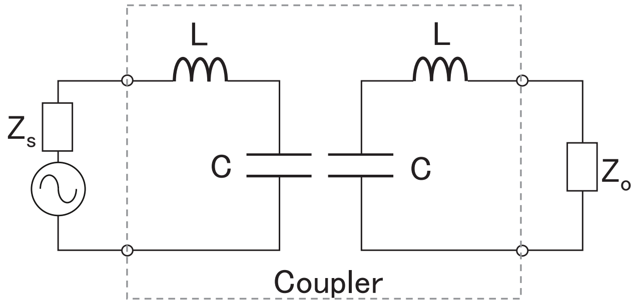

Figure 3 The equivalent circuit diagram of the electric field resonance type coupler.

The radiated noise is one of the problems of the electric field resonance type coupler WPT. Figure 4 shows the state of the electric lines of force extending around the electric field resonance type coupler as an example of the electromagnetic field analysis. In this way, since the electric field is a divergence field, the electric lines of force extend to the surroundings and couples with the structure around the coupler and the ground.so that the leakage electric field is easily generated. Therefore, a common mode loop through the earth occurs and the generation of the unintended radiated noise becomes a problem.

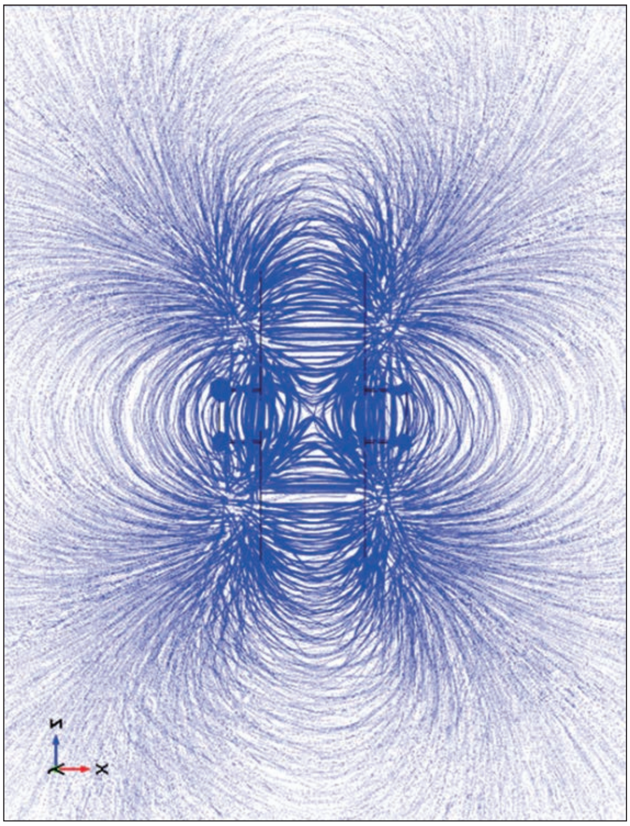

Figure 4 The state of the electric lines of force occurring around the electric field resonance type coupler.

One method of preventing this is to enclose the coupler with a metallic shield box having an aperture. An unnecessary coupling with the surroundings can be prevented by the shield box. On the other hand, since the coupling between the coupler and the shield becomes stronger, the coupling between the transmission and the reception becomes weak so that the problem that the transmission distance becomes short will occur.

3.2.2 The transmission properties of the electric field resonance type coupler

The external view of the developed electric field resonance type coupler is shown in Figure 5. In order to suppress the unnecessary coupling with the surroundings, a coupler is placed in a metallic shield box provided with an aperture. Table 1 shows the specifications of the electric field resonance type coupler. The electrode size and the number of turns of the coil are adjusted to resonate at a frequency of 13.56 MHz.

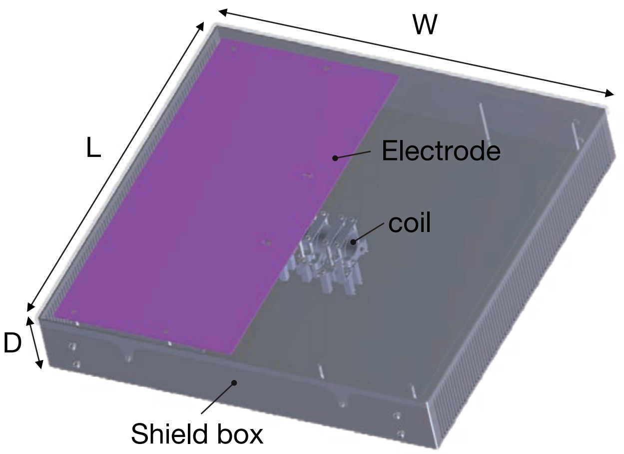

Figure 5 The external view of the electric field resonance type coupler with a shield box.

Table 1 The specifications for the electric field resonance type coupler.

Item	Specification value
Frequency	13.56 MHz
Characteristic impedance	50 Ω
Distance between couplers	77 mm
External dimensions	L480 x W180 x D80 mm
Volume	18.4 litter

The frequency characteristics of the electric field resonance type coupler were measured using a network analyzer (Agilent Technologies, E 5061 B). Figure 6 shows the frequency characteristics of the transmission efficiency η 21 (= $|S21|^2$) and the reflection loss η 11 (= $|S11|^2$) measured using the network analyzer (Agilent Technologies, E 5061 B). From this, it can be understood that the high transmission efficiency of 92.6% is shown at the distance of 77 mm between couplers and a frequency of 13.56 MHz. Since the consistency is obtained at that frequency and there is almost no reflection loss, it means that the insertion loss of 7.4% is generated. Most of this loss appears as a heat generated in the coil. Since the coil uses an air core solenoid coil and there is no iron loss due to the ferrite material, etc., the copper loss of the coil itself and the high frequency loss are considered to be the main factors. In order to further improve the efficiency of the electric field resonance type coupler, it is necessary to reduce the loss of the coil portion.

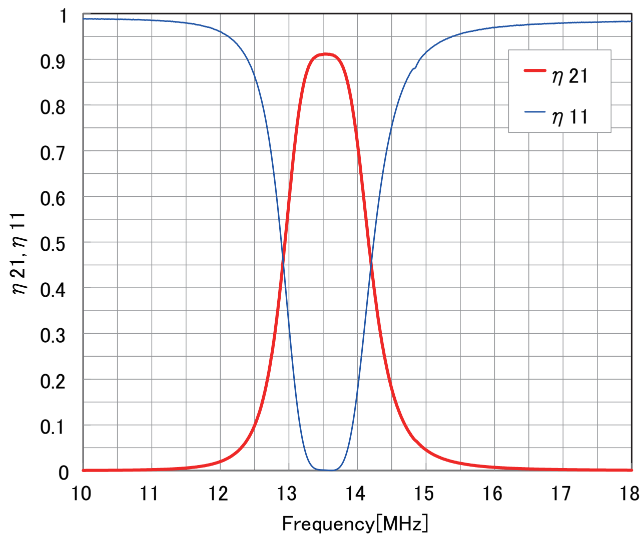

Figure 6 The frequency characteristics of the transmission efficiency and the reflection loss of the electric field resonance type coupler.

4. THE ACQUISITION OF THE INSTALLATION PERMIT FOR THE HIGH FREQENCY UTILIZATION EQUIPMENT OF THE ELECTRIC FIELD RESONANCE TYPE WPT SYSTEM

4.1 The Specifications for the Electric Field Resonance Type WPT System

The WPT system shown in Figure 7 was constructed with the aim of obtaining the installation permit of the high frequency utilization equipment of the electric field resonance type WPT system operating at a frequency of 13.56 MHz and an output power of 1 kW. The photograph of the external view and the specifications of the WPT system constructed are shown in Figure 8 and Table 2.

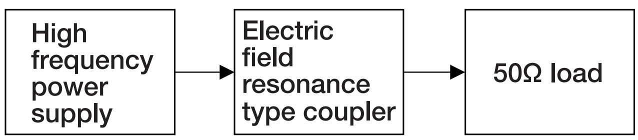

Figure 7 The block of the electric field resonance type WPT system.

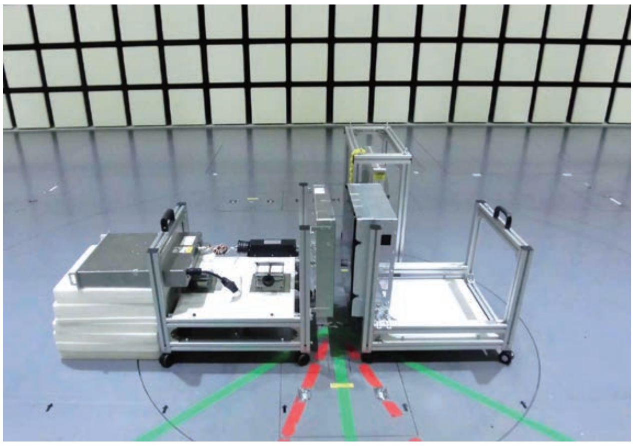

Figure 8 **The external view of the electric field resonance type WPT system.**

Table 2 **The specifications of the electric field resonance type WPT system.**

Item	Specification value
Frequency	13.56 MHz
Transmitted power	1 kW
Distance between couplers	77 mm

4.2 About the Legal Status of the Electric Field Resonance Type WPT System With a Frequency of 13.56 MHz and an Output Power of 1 kW

From the Ministry of Internal Affairs and Communications Notification No. 207 dated June 11, 2015, the special provisions on the allowable value of the EMI are stipulated for the high frequency utilization equipment other than the communication equipment in accordance with the Article 65, Paragraph 1 of the Radio Equipment Regulation. Within the following frequency bands, the maximum allowable value of the noise terminal voltage, and the magnetic field intensity and the electric field intensity due to the radiation and the unintended radiated emissions is not defined.

- 13.56 MHz ± 6.78 kHz
- 27.12 MHz ± 126.72 kHz
- 40.68 MHz ± 20.34 kHz
- 2450 MHz ± 50 MHz
- 5.8 GHz ± 75 MHz
- 24.125 GHz ± 125 MHz

These frequencies correspond to the ISM band in Japan and are frequency bands allocated for the general purpose in the industrial, scientific and medical fields. The regulations on the radio interference, the electromagnetic compatibility and etc., are relaxed.

As shown in Figure 1, since the electric field resonance type WPT system with a frequency of 13.56 MHz and an output power of 1 kW falls under the high frequency utilization equipment, it is necessary to satisfy the allowable value of the EMI in accordance with the Article 65, Paragraph 1, Item 4 of the Radio Equipment Regulation. However, since the fundamental frequency of 13.56 MHz and its harmonic frequency of 27.12 MHz and 40.68 MHz are included in the ISM band and the maximum allowable value is not defined, it is necessary to satisfy the above-mentioned allowable value of the EMI excluding these frequencies.

4.3 The EMI Measurement of the Electric Field Resonance Type WPT System

In order to obtain the permit for the installation of the high frequency utilization equipment, the EMI measurement shall be carried out at the certified site of the EMI test to indicate that the allowable value is satisfied. It is necessary to carry out the EMI measurement of the radiated noise and the conducted noise as a performance verification test of the high frequency utilization equipment regulation.

We conducted the EMI measurements at the certified site based on the domestic standards[5] in compliance with the international standard CISPR 11 version 5.1. Table 3 shows the EMI measurement conditions of the performance verification test of the high frequency utilization equipment regulations. These measurement results are shown in Figure 9 to Figure 16. For each measurement result, the allowable value in accordance with the Article 65, Paragraph 1, Item 4 of the Radio Equipment Regulation and as a reference, the allowable value of the ISM band equipment Class A Group 2 specified by CISPR 11 are noted together. Equipment Class A Group 2 is intended for the utilization in an industrial environment and is an ISM RF equipment that intentionally generates and uses the radio frequency energy.

Figure 9 shows the state of the magnetic field intensity measurement using a loop antenna. The magnetic field intensity was measured at a separation distance of 10 m

Table 3 **The conditions for the EMI measurement.**

	Measurement target	Unit	Measuring equipment	Lower limit frequency	Upper limit frequency	Detection mode	Measuring environment
Conducted noise	Conducted noise emission	dBuV	LISN	150 kHz	30 MHz	AV	Shielded room
		dBuV	LISN	150 kHz	30 MHz	QP	Shielded room
Radiated noise	Magnetic field intensity	dBuA/m	Loop antenna	150 kHz	30 MHz	QP	Anechoic chamber, 10 m separation
	Electric field intensity	dBuV/m	Biconical antenna	30 MHz	300 MHz	QP	Anechoic chamber, 10 m separation
	Electric field intensity	dBuV/m	Log-periodic antenna	300 MHz	1000 MHz	QP	Anechoic chamber, 10 m separation

between the antenna and the Equipment Under Test (EUT) and a frequency of 150 kHz - 30 MHz. Figure 10 shows the chart data of the magnetic field intensity measurement result and the allowable value of the QP value (quasi-peak value detection). The chart data shows the measurement results of the QP value and PK value (peak value detection) for each rotation angle of the loop antenna (0, 45, 90, 135 deg.; for the convenience of the data display, data of the 135 deg. are not described here,). Peaks are seen at the fundamental frequency of 13.56 MHz and the second harmonic frequency of 27.12 MHz, but these are excluded because they are included in the ISM band. It is understood that the magnetic field intensity is suppressed sufficiently low against the allowable value. In addition, strictly speaking, in the magnetic field intensity measurement, it is necessary to rotate the turn table on which the EUT is placed for each rotation angle of the loop antenna, to find the condition that maximizes the magnetic field intensity, to acquire the point data, and to show that the point data does not exceed the allowable value. In this measurement, it is confirmed that the point data also does not exceed the allowable value.

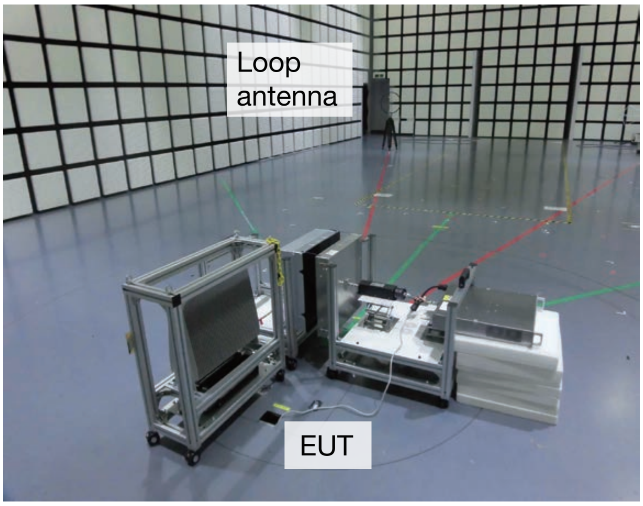

Figure 9 The state of the magnetic field intensity measurement using a loop antenna (measurement distance; 10 m).

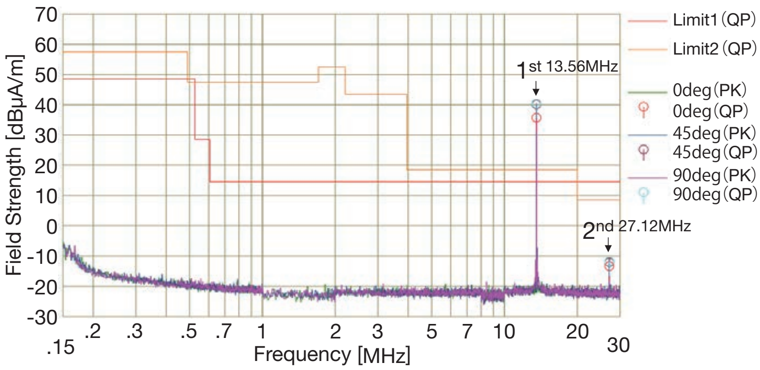

Figure 10 The result of the radiated noise.
Magnetic field intensity measurement (150 kHz - 30 MHz)
Limit 1: Radio Equipment Regulations Article 65, Paragraph 1, Item 4 (2) I 10 m
Limit 2: CISPR 11 Group 2 Class A 10 m

Figure 11 shows the state of the electric field intensity measurement using a biconical antenna and a log-periodic antenna. The electric field intensity measurement was performed at a separation distance of 10 m between the antenna and the EUT and at a frequency of 30 - 1000 MHz. As explained in Section 3.2.1, the electric field resonance type WPT easily couples with the surrounding structure and it becomes an antenna even at an unintended frequency so that the radiated noise becomes a problem. Figure 12 shows the chart data of the electric field intensity measurement result and the allowable value of the QP value when the measures for the radiated noise are insufficient. The chart data show the measurement results of the QP value and the PK value for each rotation direction of the antenna (horizontal direction, vertical direction). Many peaks of the odd-order multiple harmonic waves of 13.56 MHz, which is the fundamental frequency, can be seen. Also, in the band of 200 MHz or more, it can be understood that many peaks exist at the frequencies other than the harmonic components. This is the noise due to the common mode current caused by the unintended coupling. In the electric field resonance type WPT, it is necessary to take sufficient measures against such unnecessary radiated emission. Figure 13 shows the electric field intensity measurement result after the measures for the noise. Although the peaks of the odd-order multiple harmonics wave of 13.56 MHz, which is the fundamental frequency, can be seen, it can be understood that it does not exceed the allowable value (The third harmonic wave 40.68 MHz is excluded because it is included in the ISM band.). In addition, many peaks, which exist even in the band of 200 MHz or more, disappeared and it can be understood that the unnecessary radiated emission was suppressed. In addition, strictly speaking, in the electric field intensity measurement, it is necessary to rotate the turn table on which the EUT is placed and to change the height of the antenna, to find the condition that maximizes the electric field intensity, to acquire the point data and to show that the point data does not exceeded the allowable value. In this measurement result, it is confirmed that the point data also does not exceed the allowable value.

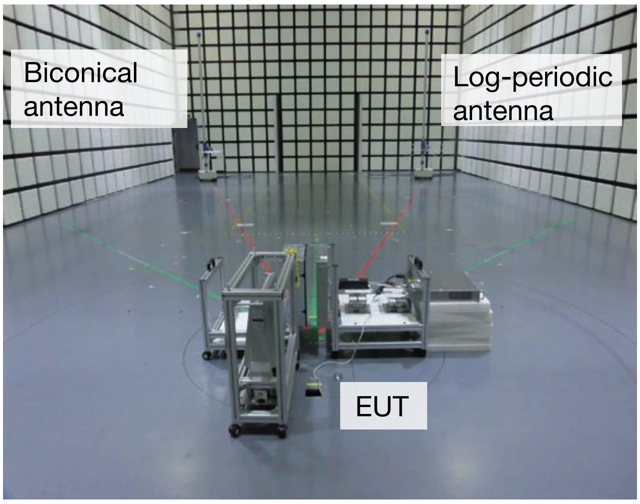

Figure 11 The state of the electric field intensity measurement using a biconical antenna and a log-periodic antenna (measurement distance 10 m).

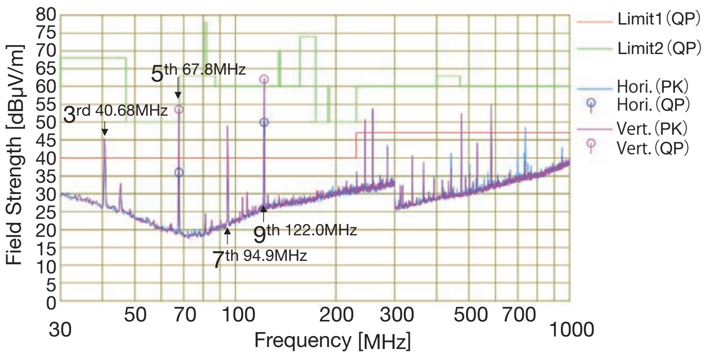

**Figure 12 The radiated noise measurement result before the measures for the radiated noise.
Electric field intensity measurement (30 – 1000 MHz)
Limit 1: Radio Equipment Regulations Article 65, Paragraph 1, Item 4 (3) 10 m
Limit 2: CISPR 11 Group 2 Class A 10 m**

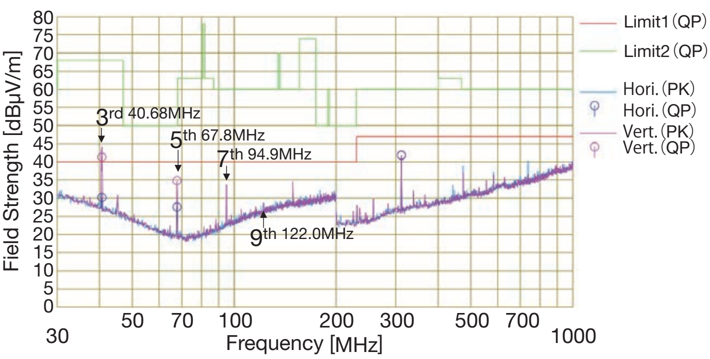

**Figure 13 The radiated noise measurement result after the measures for the radiated noise.
The electric field intensity measurement (30 – 1000 MHz)
Limit 1: Radio Equipment Regulation Article 65 (1) Item (iv) (3) 10 m
Limit 2: CISPR 11 Group 2 Class A 10 m**

Figure 14 shows the status of the conducted noise emissions measurement using the LISN. The conducted noise emissions measurement was performed at the power supply terminal at the frequency of 150 kHz - 30 MHz. Since the single-phase power supply is used in this measurement, L phase (Live ungrounded side) and N phase (Neutral grounded side) measurements are performed. Figure 15 and Figure 16 show the chart data of the measurement results of the conducted noise emissions and the allowable value of the QP value and the AV value (average value detection). The chart data show the measurement results of the QP value and the AV value. Peaks are seen at the fundamental frequency of 13.56 MHz and the second harmonic of 27.12 MHz, but these are excluded because they are included in the ISM band. It can be understood that the conducted noise emissions are suppressed sufficiently lower than the allowable value. In this measurement also, it is confirmed that the allowable value is not exceeded in the point data.

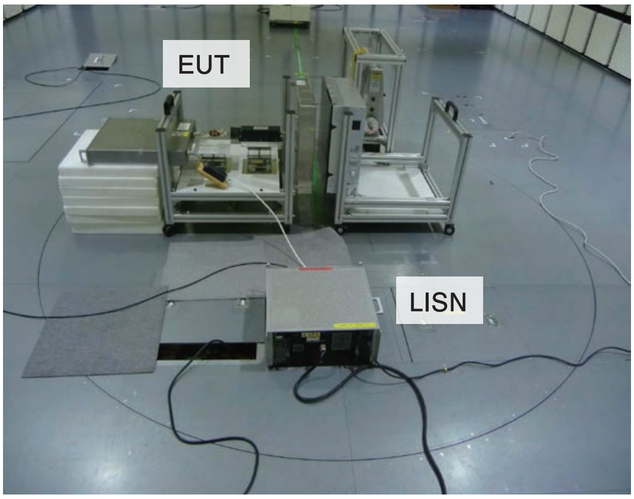

Figure 14 The status of the conducted noise emissions measurement using a line impedance stabilization network (LISN).

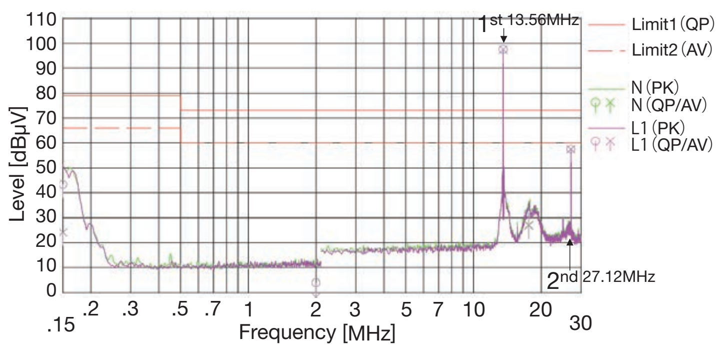

**Figure 15 The measurement result of the conducted noise emissions. Interference wave voltage measurement at the power supply terminal (150 kHz - 30 MHz)
Limit 1: Radio Equipment Regulation Article 65, Paragraph 1, Item 4 (1) QP(20 kVA or less)
Limit 2: Radio Equipment Regulations Article 65 (1) (iv) (1) AV**

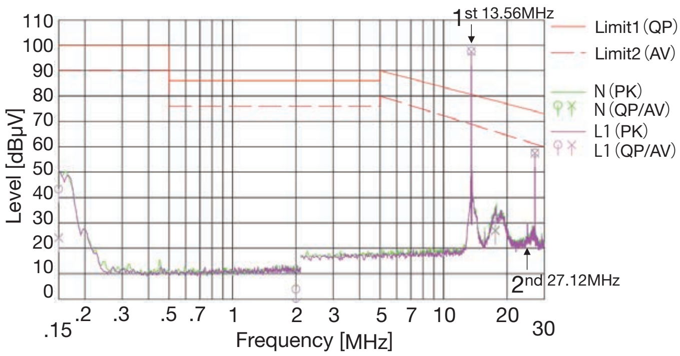

Figure 16 The measurement result of the conducted noise emissions .
Limit 1: CISPR 11 Group 2 Class A QP
Limit 2: CISPR 11 Group 2 Class A AV

From the above results, it can be understood that each noise value in accordance with the Article 65, Paragraph 1, Item 4 of the Radio Equipment Regulation is below the allowable value of the EMI except for the ISM band. We were able to confirm the ability that the developed electric field resonance type WPT system with a frequency of 13.56 MHz and an output power of 1 kW satisfies the high frequency utilization equipment regulations.

5. CONCLUSION

The EMI measurement of the electric field resonance type WPT system with a frequency of 13.56 MHz and an output power of 1 kW was carried out. We were able to confirm the ability to satisfy the EMI allowable value specified by the high frequency utilization equipment. We submitted this measurement result together with the permit application form of the high frequency utilization equipment and we were able to obtain the installation permit of the high frequency utilization equipment.

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