



Article

85 kHz Band 44 kW Wireless Rapid Charging System for Field Test and Public Road Operation of Electric Bus

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Abstract: Wireless charging technology for heavy-duty vehicles has been investigated for eco-friendly transportation. We present a new wireless power transfer system for 44 kW rapid charging of electric buses. The transmission distance between the charging pads is from 10 to 13 cm. The large air gap can be fulfilled by the ordinary kneeling function, equipped on most low-floor buses. Dual-block parallel transmission with opposite-phase-current-feeding suppresses magnetic radiation. The system operates in the common 85 kHz band with the light-duty vehicle system. The result of the field test and the public road operation of two electric buses confirm the CO₂ reduction effect described.

Keywords: wireless battery charging; electric bus; magnetic emission; rapid charging; CO₂ reduction

1. Introduction

The deployment of various sorts of electric vehicles, such as plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), including light-duty vehicles and heavy-duty vehicles, such as electric buses and cargo trucks, is expected to be an important development contributing to the emergence of a low-carbon society. In Japan, the national and local governments are financially assisting the deployment of electric buses, and thus electric buses are being actively operated in many municipalities, as well as by private-sector companies. Regular operations in the past few years in Nagano City and Kawasaki City are among the most recent successful public-sector applications [1,2]. A similar application example in Putrajaya, Malaysia, is also ongoing [3].

Wireless charging technology [4–8] for light-duty vehicles has been actively researched and SAE (Society of Automotive Engineers) International Task Force J2954 has been leading its standardization activities. In April, 2019, the task force released its second Recommended Practice (RP2) [9], based on their extensive testing results. This RP2 will be used for interoperability, performance, and emissions testing, where a single standard coil-set is chosen for WPT (Wireless Power Transfer) power class 1, 2 and 3, up to 11 kW using circular topology.

Wireless charging technology for heavy-duty vehicles has also been actively investigated with a view to accelerating deployment of eco-friendly public transportation. There have been several examples of field operation of wireless battery charging for electric buses at parking spaces. They are usually able to transfer several tens or even hundreds of kilowatts to charge a large-capacity battery mounted on an electric bus. SAE International recently restarted its J2954 sub-task force, “High Power”, and continues its discussion to draft a technical information report of high-power wireless charging systems for heavy duty vehicles.

However, there are several concerns regarding conventional wireless charging systems.

First, conventional systems employing electromagnetic induction need good alignment of charging pads on both sides, i.e., in the parking space and on-board. Typically, misalignment should be less than 5 cm. Even a professional bus driver often has difficulty in parking an electric bus so as to satisfy this condition.

The second problem is magnetic radiation or emission with high-power transmission. To reduce the radiation, the air gap between the charging pads on both sides should be very narrow, typically 1.5 to 4 cm. These conventional systems usually mount an additional bulky mechanism to lower and lift the charging pad of an electric bus. Recent magnetic resonance wireless power transfer technology can enlarge the air gap between the charging pads with moderate transmission efficiency. However, under the larger air gap condition, the magnetic radiation usually exceeds the regulation in Japan.

In addition, the operation frequency bands of the conventional systems, such as 20 kHz, are not identical to the 85 kHz band, the candidate frequency for wireless charging systems for light-duty vehicles. In 2014, Task Force J2954 of SAE International agreed that the 85 kHz band should be selected. The agreement on selection of the 85 kHz band was based on extensive research on the current usage status of plural candidate frequency bands as well as compatibility with other radio systems. Additionally, the usage of the common 85 kHz band for wireless charging systems of heavy-duty vehicles will facilitate the rapid introduction of the system by avoiding the difficult consensus-building to allow other frequency bands for this purpose. Moreover, considering future mass production of wireless charging systems for light-duty vehicles [4], which will transfer electric power up to 22 kW, the semiconductor devices, as well as the magnetic materials that would be used for the light-duty systems of the common 85 kHz band, would lead to more cost-efficient systems for heavy-duty vehicles, since common devices and materials would be applied in both systems.

We present a new wireless power transfer system using the 85 kHz band for 44 kW rapid charging of electric buses, which is similar to the current conductive rapid charger. The result of its field test and the public road operation of two electric buses [10] to confirm the CO₂ reduction effect is also described.

2. Materials and Methods

In this section, the principle specifications and block diagram of the 85 kHz band for 44 kW wireless charging system for electric buses are shown. As a method to suppress unwanted magnetic radiation, a dual-block parallel transmission with opposite-phase-current feeding is introduced. The diagonal placement of two sets of solenoid pads is also described as a method to reduce interference coupling between the two sets.

2.1. Principal Specification of 85 kHz Band 44 kW Wireless Charging System for Electric Buses

The principal specifications of the system [11] are listed in Table 1. The system employing magnetic resonance can achieve the robustness against lateral and longitudinal misalignment of charging pads

in both sides. Both ± 10 cm misalignment in the right-left direction and ± 10 cm misalignment in the front-rear direction are allowed. The transmission distance between the charging pads is from 10 cm to 13 cm. The large air gap can be easily provided by the ordinary kneeling function equipped on most low-floor buses.

Table 1. Specifications of 85 kHz band 44 kW wireless rapid charging system.

Item	Specification
Input power	3 phase 200V
Transfer frequency	81.93 kHz in 85 kHz band
Receive power	44 kW
Misalignment tolerance of charging pads	± 10 cm min.
Transmission distance between charging pads	10 thru 13 cm
Total power transmission efficiency	>85%
Configuration of charging pads	Two sets of transmit and receive charging pads
Radio communication for control	2.4 GHz wireless LAN

2.2. Block diagram of 85 kHz band 44 kW Wireless Charging System

Figure 1 shows a block diagram of the developed wireless power transmission system for wireless charging of electric buses.

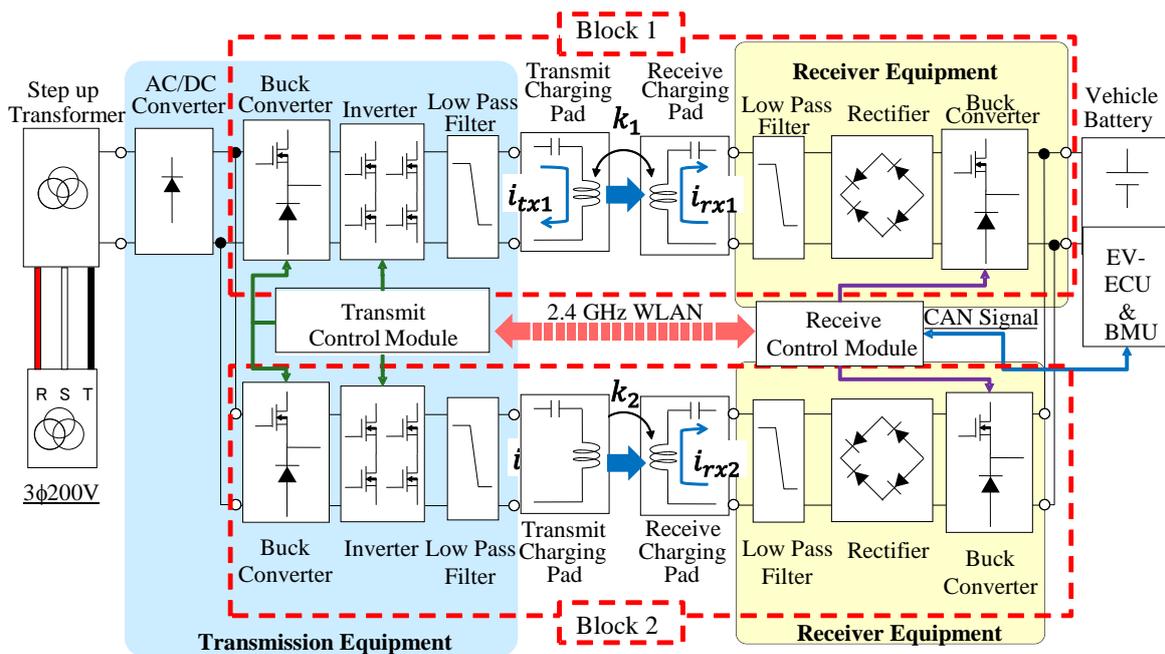


Figure 1. Block diagram of dual-block 44 kW wireless rapid charging system.

A transmitting circuit generates two-channel 85 kHz band high-power signals with opposite phase from a commercial power source. An AC/DC converter feeds DC power to two buck converters for parallel transmission and adjustment of DC voltage input to 85-kHz inverters. SiC half-bridge modules are used in 85-kHz inverters for better power efficiency. The low pass filters reduce the emission of harmonics frequency of 85 kHz through the transmitting charging pads.

A receiving circuit rectifies 85 kHz band high-power signals to DC and charges the battery. The rectifier also employs a high-power SiC full-bridge. The low pass filter in the receiving side is mainly intended to decrease the harmonic emissions back from the rectifier through the receiving charging pad. The buck converter adjusts its output DC voltage to meet the requirements of the vehicle

battery. The control circuit uses 2.4 GHz wireless LAN for communication between transmitting equipment and receiving equipment.

The respective transmitting pads and receiving pads embed solenoid coils with ferrite cores and compensation capacitors. The flush-mounted transmitting pads and the receiving pads mounted in the bus are molded by epoxy resin. This resin moldings were intended for water-proofing property, good heat conduction, and sufficient firmness against trampling by buses.

The system employing buck converters in the transmitting and receiving circuits can have robustness against lateral misalignment of the charging pads on both sides by adjusting the output voltages of the buck converters. Both ± 10 cm misalignment in the front–rear direction and ± 10 cm misalignment in the right–left direction are allowed.

The details on the design method and the SPICE (Simulation program with Integrated Circuit Emphasis) verification simulation results on power electronics in the transmitting circuit and receiving circuit are described in [12].

2.3. Dual-Block Parallel Transmission for Suppression of Magnetic Radiation

There are two reasons to use dual-block parallel transmission for the proposed system. One of the reasons to use the parallel configuration is the reduction of the required withstanding voltage of power electronics in transmission equipment and the cubic capacity of each charging pad for sufficient thermal capacity.

The second and most important reason is the cancelling of the radiated emission. The currents in the individual blocks are controlled to be the opposite phase by using two inverters [12].

Figure 2 shows the principle to cancel the radiation at the designated location in the Radio Act or similar regulations, i.e. 10 m from a pair of transmitting and receiving charging pads. The emission at around 10 m from the pair of transmitting and receiving charging pads can be approximated as the emission of a small magnetic dipole in the 85 kHz band. In the case that another small magnetic dipole is set in the opposite direction and with the same amplitude as the small magnetic dipole corresponding to the transmitting or receiving pad, the radiated emissions from the two magnetic dipoles cancel each other out and the magnetic field strength can be suppressed.

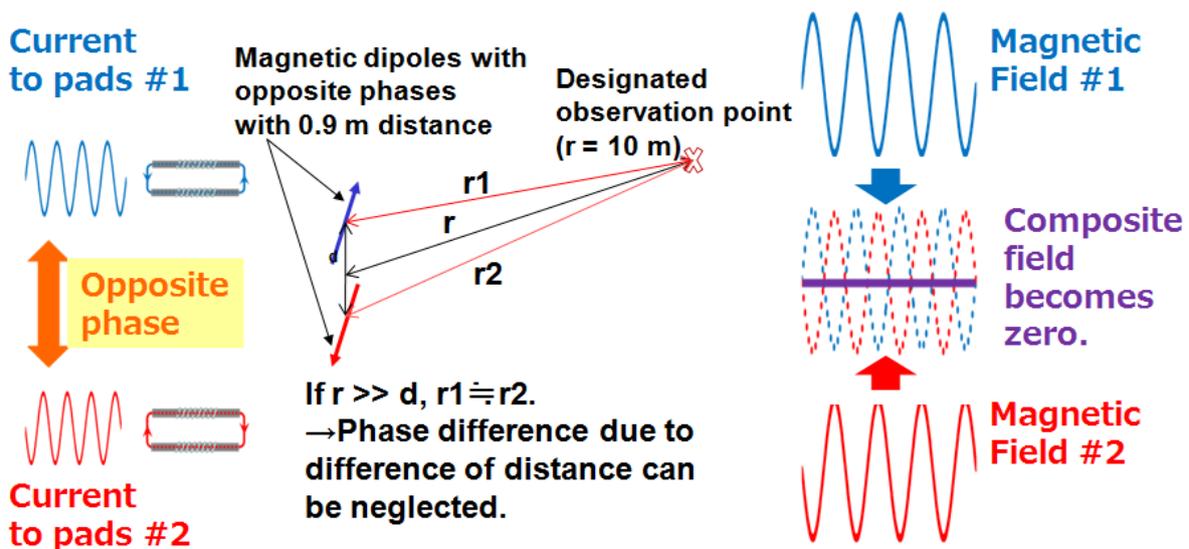


Figure 2. Opposite-phase-current feeding for suppression of magnetic radiation.

In principle, more than two coils can be used for suppression so that the vector sum of the complex magnetic field should be nearly zero. Note that the increase in the number of pads does not allow a better suppression performance, rather it will increase the complexity of control of magnitude and

phase of magnetic field from each set of pads. When dual parallel transmission sufficiently reduces the required withstand voltage and the volume of the pad, the selection of two as the number of pads is desired for simplicity.

2.4. Diagonal Placement of Two Sets of Solenoid Pads to Reduce Interference Couplings

For the inductors in the pads of the developed system, the solenoid coils are employed to obtain a higher coupling coefficient than that of the spiral coil.

A placement of the two sets of pads for the dual-block wireless power transfer system is examined in terms of radiated emission and the interference couplings between the two sets [13].

Here we denote that the transmitting and receiving pads of the first set are Pads 1 and 2, and those of the second set are Pads 3 and 4. The absolute values of coupling between Pads 1 and 2, k_{12} , and that of Pads 3 and 4, k_{34} , are desired to be large for better efficiency, while the interference couplings k_{13} , k_{24} , k_{14} , and k_{23} are unwanted and desired to be zero. This is because the interference couplings complicate the control of the receiving power level, degrade the cancelling effect of the radiated emission due to phase shift of the currents in the pads, and lower the coil-to-coil power efficiency.

If the two sets of pads are installed orthogonally, for example, the interference couplings between the pads can be reduced. However, since the direction of the magnetic dipole corresponding to the pads is not parallel, the radiated emissions of the two sets of pads cannot cancel each other out at 10 m distance.

When the two sets of pads are installed parallel, since directions of the magnetic dipoles corresponding to two sets of transmitting pads and receiving pads are parallel, the radiation emissions of the two channels can cancel each other.

At a glance, when the two sets are arranged closer, a better cancelling of the radiated emission at the designated location seemed to be derived. But we would like to note that, when the dual parallel sets of pads are unthinkingly arranged too close, the unwanted and interference couplings between the individual pads can become high.

On the other hand, when the two sets of pads are located separately to reduce the interference couplings between the dual sets, the radiated emission increases and the footprint of the dual receiving pads at a vehicle body becomes large. We should also note that the shielding by walls between the two sets of pads is difficult because of strong diffraction.

Thus, a diagonal placement of the dual sets of pads is proposed to reduce the absolute values of interference couplings. Examples of the magnetic flux of the dual sets of pads in parallel are shown in Figure 3. In Figure 3a,c, the current directions in the windings are opposite to the main flux, that is, coupling coefficients in these cases are the opposite sign; plus or minus. The positions of the dual sets of pads are changed while maintaining the parallel directions of the pads, as well as the distance between the center points of the two sets. The angle Φ is defined as shown in Figure 3b; $\Phi = 0$ degrees in Figure 3a and $\Phi = 90$ degrees in Figure 3c. The couplings coefficients between the pads are simulated by the finite element method.

The numerically simulated relationship between various angles Φ and the interference coupling coefficients k_{13} , k_{24} , k_{14} , and k_{23} are shown in Figure 4. ANSYS Maxwell is employed for the numerical simulation. The interference couplings are close to zero when the angle Φ is from 50 to 70 degrees. We utilize the null points of the interference couplings, and each block of the dual-block wireless transfer system can be controlled independently without the interference from another block. A verification measurement result of radiated magnetic emission with the proposed positions of the pads in anechoic chamber is described in [13].

The developed transmitting and receiving pad sizes are 800 mm \times 640 mm and 800 mm \times 620 mm, respectively. The angle Φ of 58 degrees and the distance between the center of the two transmitting pads of 885 mm are determined for appropriate mounting to the bus.

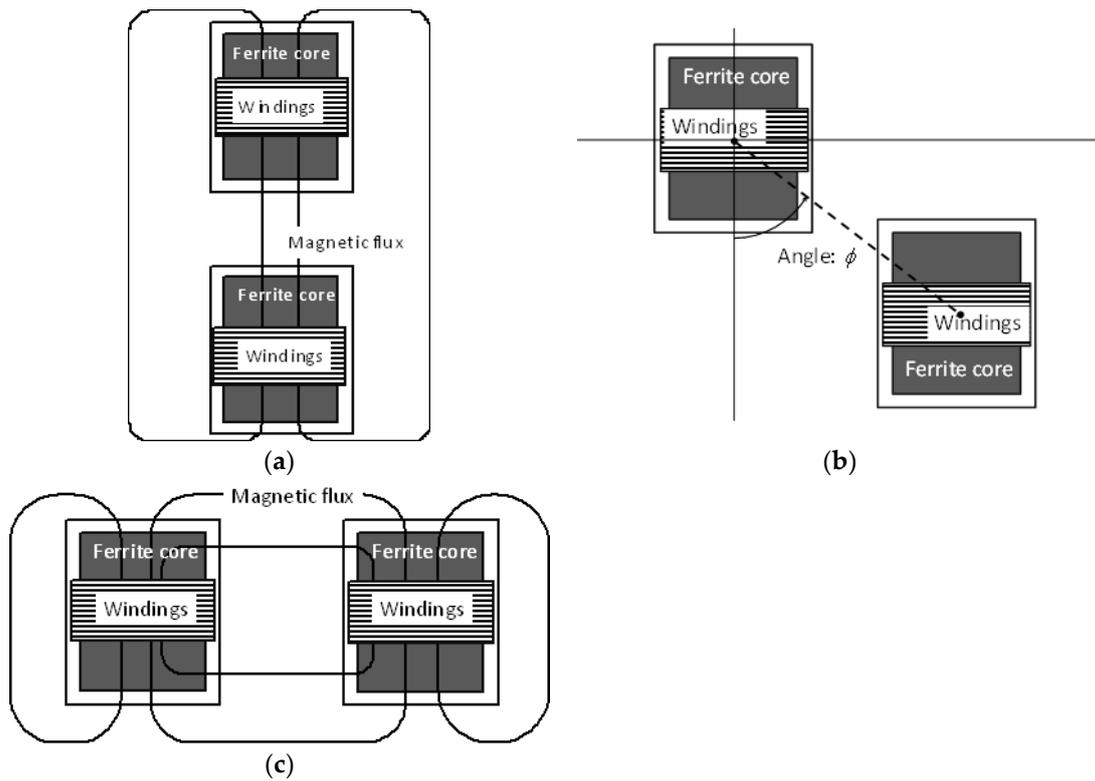


Figure 3. Mutual position of two sets of solenoid pads with mutual position angle Φ . $\Phi = 0$ degrees in (a), $\Phi = 53$ degrees in (b), $\Phi = 90$ degrees in (c).

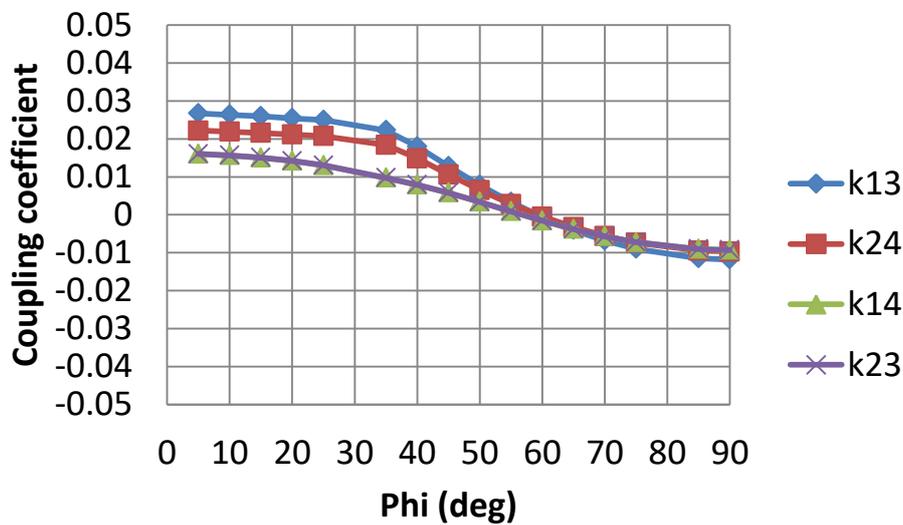


Figure 4. Simulated interference couplings with respect to $\Phi(\text{Phi})$.

3. Results

3.1. In-Situ Measurement of Magnetic Radiation from Wireless Charging System Installed in Parking Lots

3.1.1. Transmission Equipment in Parking Lot

The transmission equipment of the 44 kW wireless rapid charging system has been installed in a parking lot of a business center of ANA (All Nippon Airways Co., Ltd., Tokyo, Japan) in Kawasaki City, as shown in Figure 5. A diagonal placement of the dual sets of pads was used for reduction of interference couplings between the sets of pads as described in the previous section.



Figure 5. Transmit equipment of 85 kHz band 44 kW wireless rapid charging system.

3.1.2. Receiving Equipment Installed in Small Buses and Medium-Sized Buses

The receiving equipment has been mounted to the bottom of two buses. Figure 6 shows a small bus, which is called as “WEB3 (Waseda Electric Bus 3) Advanced” and carries a 39 kWh battery, and the receiving equipment on the bottom of the bus, and Figure 7 shows a medium-size bus, which mounts a 53 kWh battery and the equipment.

3.1.3. In-Situ Measurement of DC Charging Power, Power Efficiency and Magnetic Radiation

Figures 8 and 9 show the power, the system efficiency and the magnetic radiation of the system with the small bus, and the measured results show that the system meets the above specification. Note that the red curve denoted as Dark Noise in Figure 9 shows the spectrum without operation of the wireless charging system. Ten or more spikes in the spectrum are caused by radio broadcasting and other existing radio systems. The peak values of these spikes are unchanged, even during the operation of the wireless charger. Thus, the wireless charging system meets the regulation. Similar measurements with the medium-size bus were also conducted and confirmed adherence with the specification.

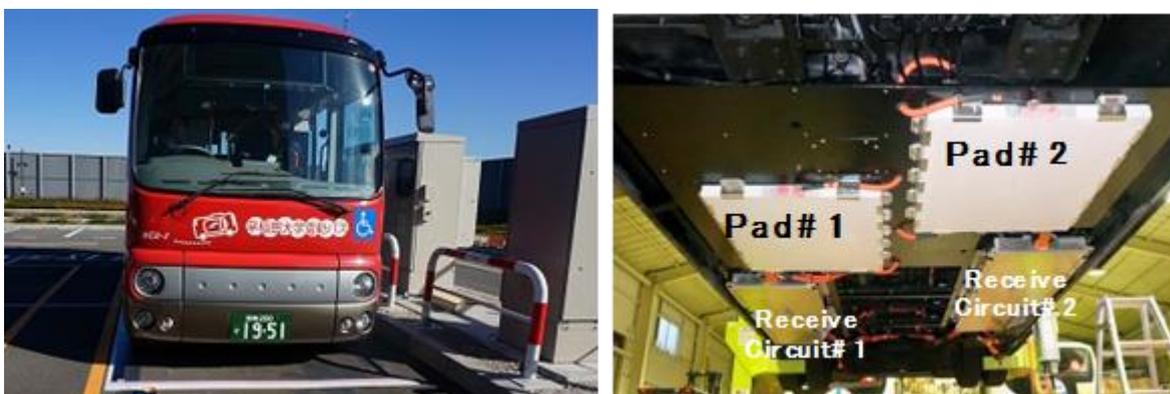


Figure 6. The Small Bus (WEB3 Advanced) and the Receive Equipment installed to the Bus.



Figure 7. The medium-size bus and the receiving equipment installed on the bus.

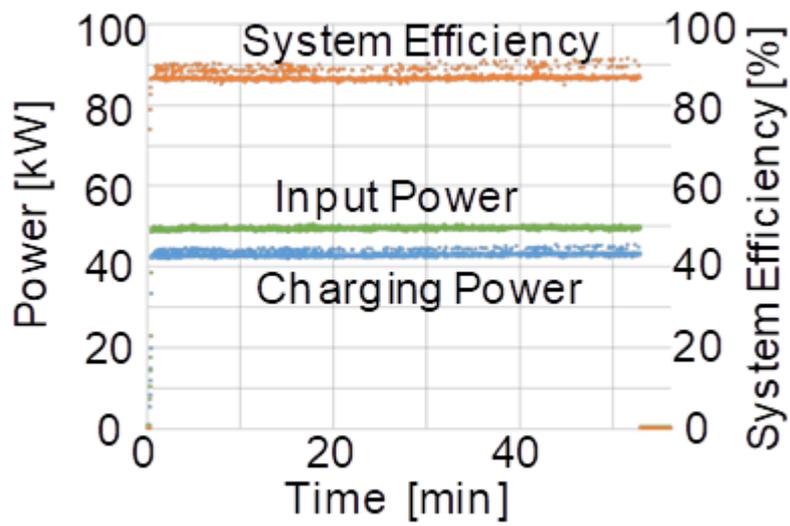


Figure 8. DC charging power and system efficiency of 44 kW wireless charging system with a small bus (WEB3 Advanced).

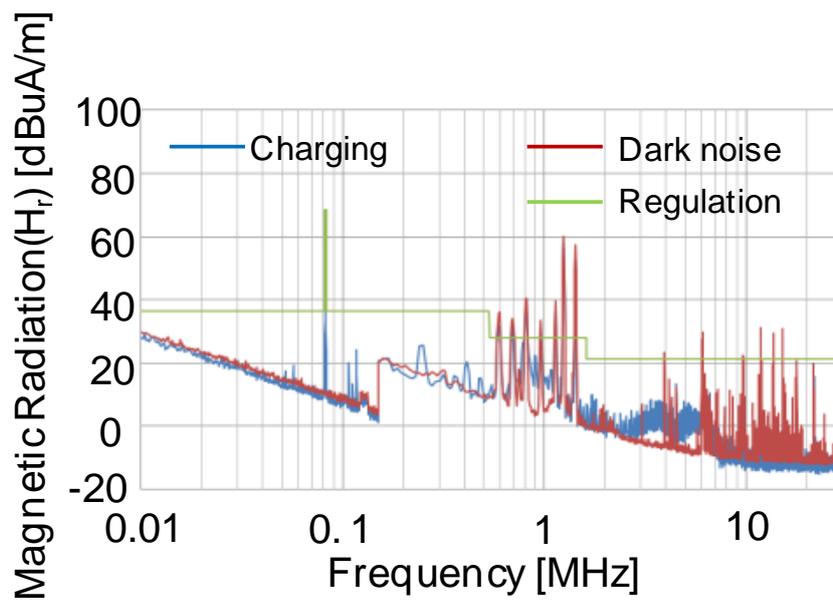


Figure 9. Magnetic radiation of 85 kHz band 44 kW wireless charging system with a small bus (WEB3 Advanced) at a distance of 10 m.

3.2. Field Test of Emulated Bus Operation on Public Roads

The field test of the emulated bus operation on public roads, including Shutoko-Expressway in the Tokyo Metropolitan Area using two electric buses was carried out from February 2016 to January 2017. The operation simulates shuttle buses for employees moving between the different worksites of an enterprise. Figure 10 shows the field test courses.

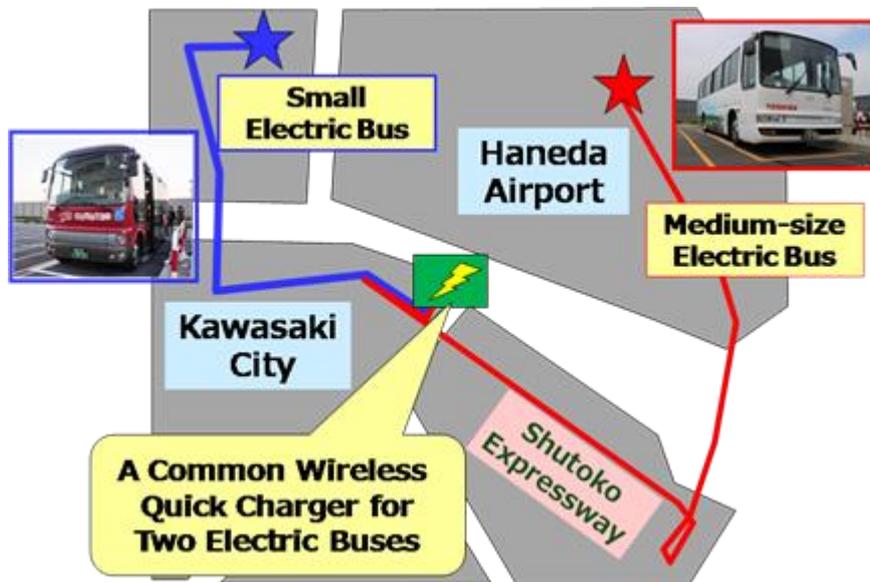


Figure 10. The field test courses in public roads around Haneda Airport and the installation site of 44 kW wireless charging system for two electric buses.

As the field tests continued for almost one year, the wireless quick charger experienced cold weather with snow, long rainy seasons, and very warm conditions under direct sunshine, but continued to operate properly. The wireless charging worked properly even when a rain layer formed on the buried transmitting pads. The water-proof property of the flush-mounted transmitting pads and the on-board receiving pads proved to be sufficient. The occasional check showed that total power transmission efficiency retains the specification value well during the field test.

Table 2 shows the overview of the field test including the charging time, the operation frequency, and the analyzed result of CO₂ emission reduction. Our detailed analysis verified that using the buses to replace standard diesel buses could cut CO₂ emissions from daily operation by up to 60%.

Table 2. Overview of result of field test.

Bus Type	Small Electric Bus	Medium-Size Electric Bus
Period	From February 2016 to January 2017	
Route	Approximately 6 km between ANA business centers in Tonomachi, Kawasaki and Higashi-Kojiya, Ota-ku, Tokyo	Approximately 11 km between ANA business centers in Tonomachi, Kawasaki and Haneda Airport
Frequency	4 round trips a day	3 round trips a day
Charge time	Approximately 15 minutes	Approximately 20 minutes
Passengers	ANA Group employees	
Effect of CO ₂ emission reduction	42%	60%

The detailed analysis results focused on the regenerative energy made by the medium-sized electric bus running on the expressway, including seasonal variation, is described in [14,15].

4. Discussion

We developed a wireless power transfer system for the rapid charging of electric buses, and confirmed this by evaluating whether the target specifications were satisfied: The maximum electric power received was 44 kW, the maximum displacement tolerance of the transmitting pads and receiving charging pads was ± 10 cm or more, and the sufficient suppression of magnetic radiation using two-block parallel transmission.

The on-site measurement results show that the 85-kHz wireless power transfer system has sufficient performance. The result of the field test of emulated operation of two different buses on public roads shows the wireless charging is quite convenient as well as safe for bus drivers.

Our analysis clarified that the CO₂ emissions from daily operations are reduced by up to 42% and 60% when the standard diesel buses are replaced by the small and medium-sized electric buses, respectively.

We now proceed with the development of a wireless charging system with a charging power of 100 kW or more to additionally reduce the charging time. This development to increase transmitting power has faced some new issues. One of the issues is apparently an efficient set of power electronics for transmitting and receiving circuits. Another issue is the need for additional reduction technology to be used with the present two-block parallel transmission. The development of such reduction technology is also ongoing. The result will enable opportunity charging during ordinary bus operations in dense urban areas.

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