Input Impedance Matched AC-DC Converter in Wireless Power Transfer for EV Charger

Keisuke Kusaka*, Jun-ichi Itoh*
* Nagaoka University of Technology, 1603-1 Kamitomioka Nagaoka Niigata, Japan

Abstract—**This paper provides experimental verifications of the AC-DC converter for an electrical vehicle (EV) battery charger which an input impedance is matched to a characteristic impedance of a transmission line. In a high-frequency wireless power transfer system such as a magnetic resonant coupling (MRC), the input impedance of the AC-DC converter in the receiving side of the wireless power transfer should be matched to the characteristic impedance of the transmission line in order to suppress the reflected power. This paper presents the fundamental characteristics of the AC-DC converter. The experimental result shows that the AC-DC converter enables a conversion from 13.56 MHz AC to DC with input impedance of 29.6+*j*0.51 Ω. Thus, the reflection coefficient is suppressed by 17.8 points compared with that of the conventional capacitor input-type diode bridge rectifier with 25 Ω of a load resistance. The suppressed reflection coefficient can reduce the reflection loss of the wireless power transfer system.**

Index Terms—**Wireless power transfer, Impedance matching, High-frequency, AC-DC converter**

I. INTRODUCTION

In recent years, wireless power transfer methods such as a magnetic induction for wireless power transfer and micro-wave wireless power transfer are increasingly studied [1-4]. In particular, a wireless power transfer method using a magnetic resonant coupling (MRC), which is reported in 2007, has been attracted in community [5-8]. The MRC has some advantages compared with the conventional wireless power transfer methods such as an electromagnetic induction and a microwave power transfer methods. First, the MRC can be operated in high efficiency in a middle-range transmitting distance such as 1 m at high efficiency over 90% with reason of characteristic constructions of transmitting coils. The transmitting efficiency is proportional to product of the quality factor Q and a coupling coefficient k between the primary and secondary coils. The transmitting coils have high quality factor Q. The high quality factor provides the high efficiency in a middle range transmission even when a coupling coefficient is small value. Note that the coupling coefficient decreases inversely with a cube of distance. Second, the declination in transmission efficiency caused by position gap is relatively small. From above-mentioned advantages, the MRC is found suitable to apply in battery chargers for electric vehicles (EV). The transmitting coil and the receiving coil are planted on the ground of parking areas, and behind of the EV respectively. The batteries are charged automatically, when the EV is parked at parking areas. Thus, the wireless power transfer system with MRC can improve the conveniences of users.

In the wireless power transfer system with MRC, the size of the transmitting coils depends on the transmitting frequency. Considering the application for a EV battery charger requires a wireless power transfer system to operate in high-frequency close to 13.56 MHz in the industry science medical (ISM) band because transmitting coils are required being small size and light weight. In this paper, 13.56 MHz is used as a transmitting frequency.

AC-DC converters in the receiving side of the wireless power transfer system have to convert from 13.56 MHz AC to DC due to the high-frequency transmission. In addition, a reflected power occurs at boundary points of the impedance in the high frequency region when impedances are difference between the input impedance of an AC-DC converter and characteristic impedance of the transmission line. In order to suppress the reflected power between the transmission line and the AC-DC converter, the input impedance of the AC-DC converter requires to be matched to the characteristic impedance. The reflected power reduces the efficiency of wireless power transfer.

In the previous studies, capacitor input-type diode rectifiers (CI-DBRs) that are performed as an AC-DC converter in the receiving side have been tested [9]. However, when the CI-DBR is used in receiving side of the high-frequency wireless power transfer system, a large reflected power occurs because the CI-DBR cannot control the input current and the input power factor. In this scheme, the input current and the input power factor depends on the load condition. Thus the input impedance fails to match with the characteristic impedance of a transmission line.

This paper proposes an AC-DC converter which the input impedance can be matched to the characteristic impedance of the transmission line without high-frequency switching. The AC-DC converter can convert from 13.56 MHz AC to DC with input impedance matching. The input impedance matching reduce the reflection loss due to the reduction of the reflection power. The first section in this paper describes the required conditions for input impedance matching of the AC-DC converter. Secondly, a construction of the AC-DC converter is presented. Thirdly, details of design method of the AC-DC converter are provided. Finally, the simulation results and experimental results are shown in order to evaluate the validity of the proposed circuit.

II. Input Impedance Matching of AC-DC Converter

Generally, all of the impedance of the circuit components including a high-frequency power supply, a transmission line and a load are matched to the one characteristic impedance in high-frequency circuits. In other words, the output impedance of the high-frequency power supply, characteristic impedances of the transmission line and input impedance of the load have same impedance. In particular, the characteristic impedance of 50 Ω is used widely because a transmission loss has a minimum value when a polyethylene is used as an insulating material in between an inner conductor and an outer conductor. Thus the 50 Ω is used throughout the paper.

Assuming that the wireless power transfer system is employed to battery charger for EV, a high-frequency AC should be converted to a DC in the receiving side of the wireless power transfer system. So, an AC-DC converter is required in the receiving side. As a result, the input impedance of the AC-DC converter including the batteries of the EV should be matched to the characteristic impedance in order to suppress the reflected power.

Generally, a characteristic impedance of a transmission line, which is reference value for input impedance of the AC-DC converter, does not include the imaginary part. It means that the 50 Ω of the characteristic impedance indicates the 50+*j*0 Ω. Therefore, input voltage and current of the AC-DC converter should be fill the following conditions.

(1) $V_{in} / I_{in} = 50\ \Omega$

(2) Input power factor is 1 ($\cos\theta = 1$)

Where, V_{in} is the fundamental input voltage of the AC-DC converter, I_{in} is the fundamental input current and θ is the phase angle between the input voltage and the input current. In a low-frequency region such as a commercial frequency, power factor correction (PFC) circuits with a PWM control are used widely. The PFC circuit enable control the input current. In other word, the input impedance of the PFC circuit can be controlled to the characteristic impedance. However, the PFC circuit which is controlled by using the PWM control needs a high-frequency switching compared with an input frequency. Thus, it is difficult to operate the conventional PFC circuit with the PWM control when the input frequency is constrained high-frequency such as 13.56 MHz by the wireless power transfer system. It is resulting that the AC-DC converter without high-frequency switching is required in the receiving side of the high-frequency wireless power transfer system.

III. Input Impedance Matched AC-DC Converter

A. Circuit Configuration

Fig. 1 indicates the proposed input impedance matched AC-DC converter. In the proposed circuit, a bi-directional boost chopper is connected at a subsequent stage of a resonant-type rectifier shown in [10-11]. The resonant-type rectifier enables the PFC operation without high-frequency switching using a resonance between an inductor and capacitors. When the load of the resonant type-rectifier is light, the resonant frequency of the circuit is presented by (1) approximately. It means that the input current flow in a path of L_1, C_1 and C_2 for most of the time in the input period.

$$f_1 \approx \frac{1}{2\pi\sqrt{LC/2}} \tag{1}$$

On the other hand, the resonant frequency closes in to (2) with increasing load because the resonant time decline.

$$f_2 \approx \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

Reference [11] used the resonant-type rectifier in the commercial frequency. However, a low-frequency operation of the resonant-type rectifier results in bulk of circuit components; the resonant inductor and resonant capacitors. In addition, the resonant capacitors should have a high rated voltage because of series resonance between the resonant inductor and resonant capacitors. Accordingly, the resonant-type rectifier is constrained to use electrolytic capacitors, which have large equivalent series resistance, as a resonant capacitor in [11]. It causes a decline of conversion efficiency of the resonant-type rectifier.

The high-frequency such as 13.56 MHz operation of the resonant-type rectifier can improve above-mentioned disadvantages. An increasing of the input frequency reduces the capacitances of the resonant capacitor. Hence, laminated ceramic capacitors which have low equivalent series resistances can be used for resonant capacitors. For this reason, a high power density and an improvement of conversion efficiency can be achieved.

On the other hand, the resonant-type rectifier has a problem with an input current control. The input impedance has fluctuation due to the load condition in the resonant-type rectifier when the resistance load is connected at subsequent stage. In order to solve the previous problem, the bi-directional boost chopper with input voltage control is connected at subsequent stage of the resonant-type rectifier. The input impedance matching is satisfied regardless of the load condition because the resonant-type rectifier is operated at one operating point due to the voltage control by the bi-directional boost chopper. Besides, the boost chopper can be operated at low switching frequency compared with input frequency because the role of the bi-directional boost chopper is stabilizing the output voltage of the resonant-type rectifier. The voltage fluctuation of the rectifier output voltage is enough small due to the large capacitance of the smoothing capacitor. For this reason, the high-frequency switching is not necessary for the boost chopper. In this paper, the bi-directional boost chopper is switched at 100 kHz. Note that, a laminated ceramic capacitor which has low parasitic inductance in the high-frequency [12] is connected in parallel to the electrolytic capacitor in order to improve a characteristic of smoothing capacitor in the high-frequency region because the rectified voltage includes the second harmonics of the input frequency of 27.12 MHz.

In the actual wireless power transfer system, the AC-DC converter is connected to the receiving coil as a power source. However, a RF power supply which has 50 Ω of output impedance is used for simplicity of experiments instead of the wireless power transfer system. Similarly a stabilized power supply is used as a simulated battery. In addition, SiC schottky barrier diodes (SiC-SBD) are used in the resonant-type rectifier. The material value of the SiC is larger than one of the Si in term of the band-gap E_g and the breakdown field strength E_B. So, the maximum operation frequency f_{max} of the 4H-SiC reach to 9.0 which is scaled based on the value of Si where the maximum operation frequency is an index of performances which is provided by material value [13]. The maximum operation frequency is defined by $f_{max} \approx \mu E_B E_g^{0.5}$. Thus the SiC devices are suitable for high-frequency operation [14].

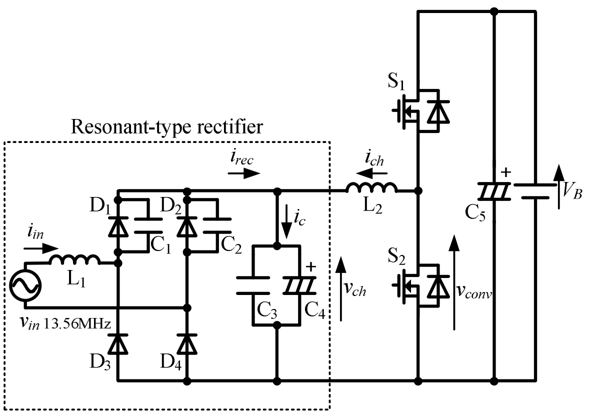


Fig. 1. Proposed input impedance matched AC-DC converter for high-frequency wireless power transfer system.

B. Control Method of Bi-directional Boost Chopper

Fig. 2 shows a control block diagram of the bi-directional boost chopper where L_{ch} is the an inductance of L_2, C_{ch} is the combined capacitance of C_3 and C_4, T_{ic} is the integral action time of an automatic current regulator (ACR) and T_{iv} is the integral action time of an automatic voltage regulator (AVR). The operating point of the resonant-type rectifier is stabilized. This is attributed to the ACR in chopper current i_c and the AVR in the rectifier output voltage v_{ch} of the bi-directional boost chopper.

The bi-directional boost chopper stabilizes the operating point of the resonant-type rectifier due to the control of the rectifier output voltage v_{ch}. In the proposed circuit, a fast dynamic response of the bi-directional boost chopper is not necessary. So, the AVR control is constructed by a PI control with 400 rad/s of natural angular frequency. Also the ACR is constructed by a PI control with 4000 rad/s in an inner loop of the AVR. The input current from the rectifier i_{rec} is deal as a disturbance.

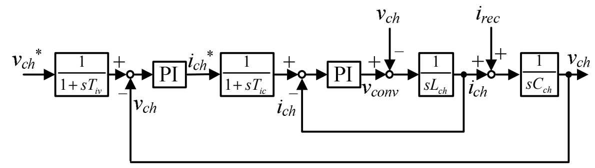
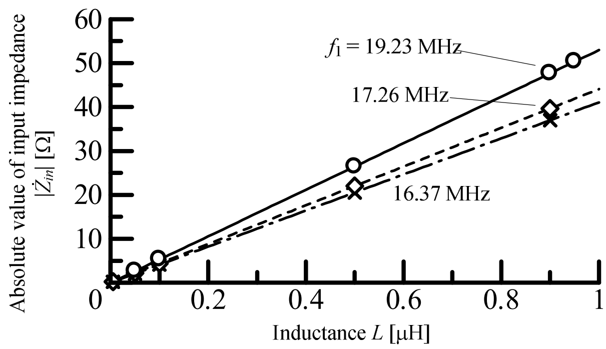


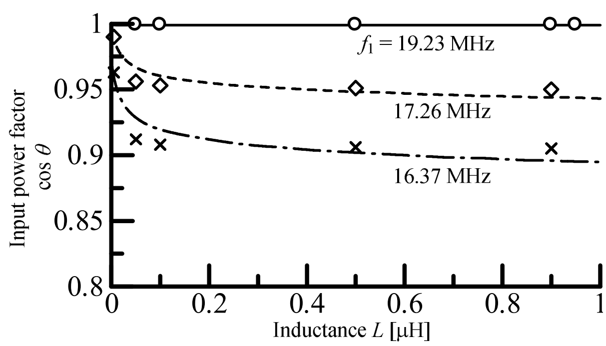
Fig. 2. Control block diagram for S_1 and S_2 in the AC-DC converter.

C. Parameters Design of the AC-DC converter

Fig. 3 presents the simulation results with input impedance variation due to the circuit parameters; inductance L and capacitance C when resonance frequency which obtained by (1) are 16.37 MHz, 17.26 MHz and 19.23 MHz. The input impedance of the resonant-type rectifier which has the bi-directional boost chopper at subsequent stage depends on the inductance L of the inductor L_1, capacitance C of C_1 and C_2, and rectifier output voltage v_{ch}. In this consideration, 223 V of the high-frequency input voltage and 500 V of the rectifier output voltage is chosen because of assuming 1 kVA wireless power transfer system. Fig. 3 (a) provides that input impedance is proportional to the inductance L. Meanwhile, the resonant-type rectifier provides a high



(a) Absolute value of input impedance.



(b) Input power factor.

Fig. 3. Variation of input impedance by circuit parameters.

input power factor when the inductance is low. Contrary to this, the input power factor is reduced progressively with increasing inductance. Furthermore, the inductance has to be designed enough large in order to ignore the effect of parasitic inductance of the circuit for implementation. The resonance frequency f_1 of 19.23 MHz can satisfy the previous conditions. Thus, the resonant inductance L = 0.95 μH, the resonant capacitance C = 0.14 nF are chosen in experiment and simulation.

IV. SIMULATION RESULTS OF THE AC-DC CONVERTER

Fig. 4 presents the simulation results of the AC-DC converter where the input voltage is 223 V, rated input power is 1 kVA. The chopper current i_{ch} and the chopper voltage v_{ch} track the referenced chopper current i_{ch}^* and the referenced rectifier output voltage v_{ch}^* respectively. The rectifier output voltage includes second harmonics from the input frequency because the capacitor C_3 is charged by the rectifier current i_{rec}. The difference of the impedance between the capacitor C_3 and L_2 allows the rectifier current to flow into only the capacitor C_3.

Focusing on the Fig. 4, the input current with a sinusoidal waveform of the AC-DC converter is obtained due to the rectifier output voltage control. Additionally, the input power factor of the AC-DC converter close in to 1 of the fundamental input power factor approximately. Incidentally, an absolute value of 51.9 Ω of the input impedance $|\dot{Z}_{in}|$ is calculated from simulation results; a fundamental input voltage is 223V, a fundamental input current is 4.29 A. The input impedance focuses attention on an fundamental component because the wireless power transfer with high quality factor Q enable a power transmitting without harmonics components.

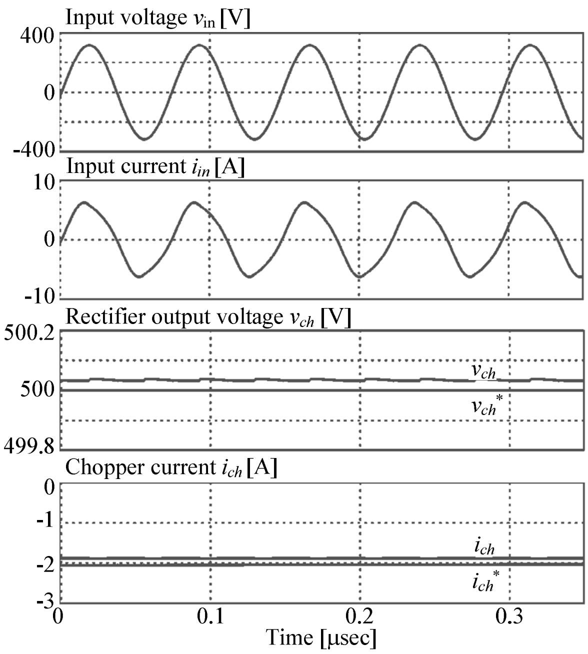


Fig. 4. Operation waveforms of the proposed AC-DC converter in simulation.

Following previous statements, it is confirmed that the input impedance of the AC-DC converter is 51.9+j0 Ω. The input impedance includes an error of 1.9 Ω compared with the characteristic impedance of the coaxial cable since the characteristic impedance of a coaxial cable is 50+j0 Ω. However, an error of 1.9 Ω means that reflected power occur against a travelling power at reflection coefficient Γ = 1.8%. In other words, a 1.8 % of travelling power which is outputted from high-frequency power supply does not be reached to a load.

A reflected power with using a CI-DBR as an AC-DC converter in the receiving side has fluctuation from 11.6% to 22.2% due to the load condition [9]. Hence, the reflected power can be suppressed up to 20.4 points with proposed AC-DC converter. The suppressing of reflected power can reduce the reflection loss of the wireless power transfer system.

V. EXPERIMENTAL RESULTS OF THE AC-DC CONVERTER

A. Experimental Setup

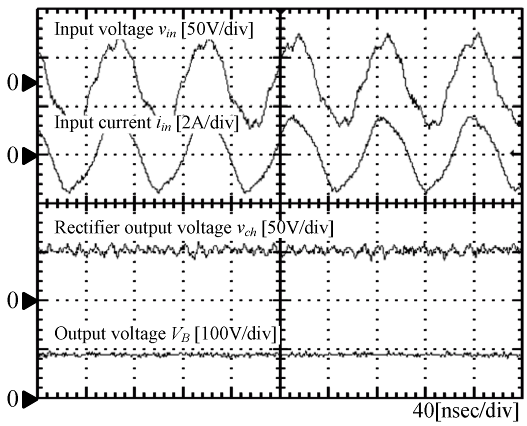
Experimental verifications are shown in this chapter. Table 1 provides circuit parameters for the experimental setup. The resonant capacitors are modified from 140 pF to 150 pF for reason of convenience of procurement. Moreover, the inductor L_2 which is made by authors from an electrical steel sheet core. Note that the bi-directional boost chopper in the proposed AC-DC converter is operated in open-loop control for simplicity. The AC-DC converter; especially the part of the resonant-type rectifier is mounted on the printed circuit board (PCB) in order to cut down the effects of parasitic inductance and parasitic resistance between the circuit components. In particular, the parasitic inductance of a wire which is used in series to resonant inductance affects the input impedance. For this reason, the resonant-type rectifier should be mounted with keeping in mind parasitic inductances.

Table 1. Circuit parameters and conditions for the experimental setup.

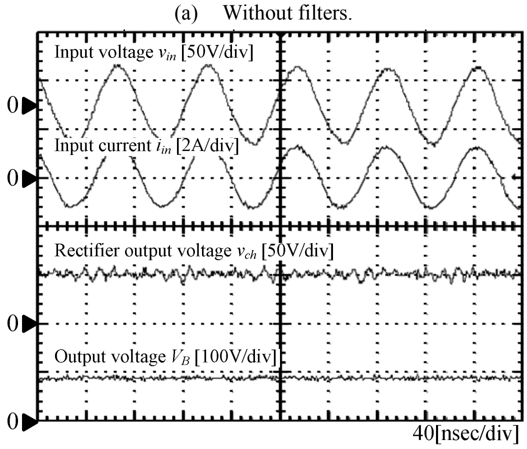
Items		Manufactures	Model number	Value
MOSFET	S_1 S_2	Vishay	IRFB11N50APBF	500 V 11 A
Diode	D_1-D_4	Cree	C3D08060A	600 V 8 A
Inductor	L_1	TDK	VLF10040T-1R5N8R9 (Remodeled)	950 nH
	L_2	-	-	2.3 mH
Capacitor	C_1 C_2	TDK	C3216C0G2J151JT	150 pF
	C_3	TDK	CKG57NX7R2J474M	470 nF (in parallel)
	C_4	nichicon	UPW2V221MRD	220 μF (in parallel)
	C_5	BHC Components	ALS30A221DB450	220 μF

B. Experimental Waveforms

Fig. 5 (a) presents the operational waveforms of the proposed AC-DC converter where the simulated battery voltage V_B is set to 90 V. Fig. 5 (b) provides the operational waveforms with Low pass filters (LPF). The input voltage and input current are indicated through LPF. Note that the LPF which has cut-off frequency of 20 MHz is implemented in the oscilloscope. The experimental results show that the input current achieves a sinusoidal waveform with small distortion. Additionally, the input current has similar characteristics to the result which is obtained by using the simulation. Besides, DC voltages of the rectifier output voltage v_{ch} and the output voltage V_B are obtained. It means that the AC-DC converter enable a conversion from 13.56 MHz of AC to DC without high-frequency switching. Note that, the input voltage distortion results from noises which immix into an input stage of the high-frequency power supply which used as instead of output coils of wireless power transfer system. From the experimental waveforms with LPF shown in (b), the low-frequency components up to 20 MHz become sinusoidal waveforms roughly, and it can be achieved unity input power factor.



(a) Without filters.



(b) With filters (cut-off frequency is 20 MHz).

Fig. 5. Experimental waveforms of the proposed AC-DC converter.

C. Harmonics analysis

Fig. 6 indicates the harmonics analysis results of the input voltage and input current of the AC-DC converter in experiments. The harmonic analysis is had to use with an oscilloscope (Tektronix, TDS5054B) in order to inspect experimental waveforms. The analysis results shown in fig. 6 are scaled on the basis of amplitude at 13.56 MHz. Additionally, a sampling frequency of the oscilloscope is 1.25 GHz. Note that, the probes; a differential probe (Tektronix, P5205) and a current probe (Tektronix, TCP305), which are used in these experiments, provide a limitation to the frequency bandwidth at 100 MHz. For this reason a harmonics component over 7th can be only become reference values. The input current harmonics is suppressed less than -20 dB in the frequency bandwidth from 2nd to 20th. Thus, an input current distortion (THD) is 11.2% (reference value) in the bandwidth by 20th from a 13.56 MHz.

Focusing attention on the fundamental components of the input voltage and current, the input voltage of 19.8 V and input current of 0.67 A are obtained from harmonics analysis. It shows that an absolute value of the input impedance $|\dot{Z}_{in}|$ is 29.6 Ω. Also, 4.1 deg of phase difference between the input voltage and the input current is obtained. The phase angle presents the input power factor cos θ is 0.99. Hence, the input impedance of the proposed AC-DC converter is 29.6+j0.51 Ω. The experimental result has measurable error on the real part so the design value is 50+j0 Ω. An additional simulation results confirmed that the error occur in reason of parasitic capacitances of diodes on the upper arm in the resonant-type rectifier. A design considering the parasitic capacitor can reduce the error.

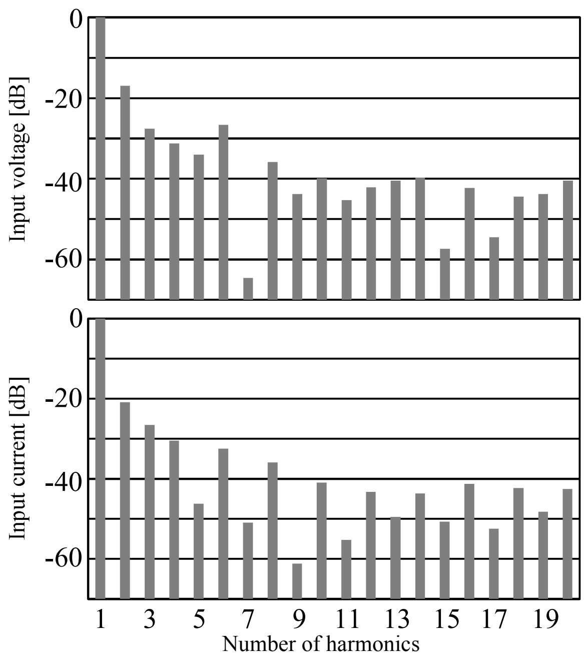


Fig. 6. Harmonics analysis of input voltage and current.

D. Reflection Coefficient

Fig. 7 presents an experimental comparison between the conventional CI-DBR with SiC-SBD and the proposed AC-DC converter, in term of the reflection coefficient. The reflection coefficient is defined from the input impedances of each circuit. It means that the reflection coefficient is the proportion of reflection power to travelling power. The reflection coefficient should be zero because the reflection power does not input into a circuit. Note that the input impedance of the conventional CI-DBR depends on the load condition. In other words the fundamental harmonic input current depends on the load. Thus the reflection coefficients are measured at each four different loads; 25 Ω, 33.3 Ω, 50 Ω and 100 Ω. To put it in perspective, the reflection coefficient with the proposed AC-DC converter has minimum value compared with using the conventional CI-DBR. Especially, the reflection coefficient is suppressed by 17.8 points compared with the CI-DBR with the load resistance 25 Ω. The experimental results show that the AC-DC converter can suppress the reflection loss which occurs at input side of the AC-DC converter in high-frequency wireless power transfer system. Furthermore, a design considering the parasitic capacitances of diodes in the resonant-type rectifier provides suppression of the reflection coefficient.

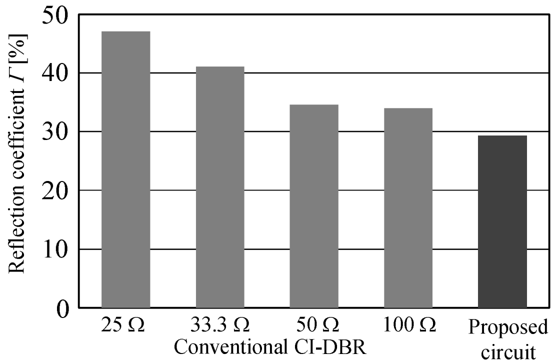


Fig. 7. Comparison of reflection coefficient between the CI-DBR and proposed AC-DC converter based on the experimental results.

VI. Conclusions

In this paper, the AC-DC converter which the input impedance can match to the characteristic impedance was proposed. The input impedance matching can reduce the reflection loss due to the reduction of the reflection power which occurs due to the impedance miss-matching between the input impedance of an AC-DC converter and characteristic impedance.

The experimental verifications confirmed that the AC-DC converter enable a conversion from high-frequency AC of 13.56 MHz to DC without high-frequency switching with input impedance matching.

The input impedance of $29.6 + j0.51$ Ω is obtained by experiments. The experimental result has a measurable error on the real part so the design value is $50+j0$ Ω. However, the reflection coefficient which indicates the rate of generation of reflected power can be reduced by 17.8 points compared with using the conventional capacitor input-type diode rectifier. Thus, it is confirmed that the AC-DC converter is valid circuit configuration for a receiving side of the high-frequency wireless power transfer system. In addition the design considering the parasitic capacitance which is reason of error can reduce the reflection coefficient more.

In the future work, the detail of the design method of the proposed AC-DC converter will be optimized.

Acknowledgment

This research was partially supported by the Japan Society for the Promotion of Science; Grand-in-Aid for Scientific Research (B), 24360106, 2012-2015

References

[1] J. O. Mur-Miranda, G. Fanti, Y. Feng, K. Omanakuttan, R. Ongie, A. Setjoadi, N. Sharpe: "Wireless Power Transfer Using Weakly Coupled Magnetostatic Resonators, *IEEE EPE*, pp. 4179-4186 (2010)

[2] T. Fujita, Y. Kaneko, S. Abe: "Contactless Power Transfer Systems using Series and Parallel Resonant Capacitors", *IEEJ Trans. D*, Vol. 127, No. 2, pp. 174-180 (2007) (in Japanese)

[3] T. Horiuchi, K. Kawashima: "Study on Planar Antennas for Wireless Power Transmission of Electric Vehicles", *IEEJ Trans. D*, Vol. 130, No. 12, pp. 1371-1377 (2010) (in Japanese)

[4] E. Waffenschmidt, T. Staring: "Limitation of inductive power transfer for consumer applications", *IEEE EPE*, pp. 1-10 (2009)

[5] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, M. Soljacic: "Wireless Power Transfer via Strongly Coupled Magnetic Resonances", *Science*, Vol. 317, No. , pp. 83-86 (2007)

[6] A. Karalis, J. D. Joannopoulos, M. Soljacic: "Efficient Wireless non-radiative mid-range energy transfer", *Annals of Physics*, Vol. 323, No. 1, pp. 34-48 (2008)

[7] S. Lee, R. D. Lorenz: "A Design Methodology for Multi-kW, Large Airgap, MHz Frequency, Wireless Power Transfer Systems", *IEEE ECCE*, pp. 3503-3510 (2011)

[8] T. Imura, H. Okabe, T. Uchida, Y. Hori: "Study on Open and Short End Helical Antennas with Capacitor in Series of Wireless Power Transfer using Magnetic Resonant Couplings", *IEEE The 35th IECON*, pp. 3848-3853 (2009)

[9] K. Kusaka, J. Itoh: "Experimental verification of rectifiers with SiC/GaN for wireless power transfer using a magnetic resonance coupling", *IEEE The 9th PEDS*, pp. 1094-1099 (2011)

[10] K. Matsui, I. Yamamoto, G. Erdong, M. Hasegawa, K. Ando, F. Ueda, H. Mori: "A Novel Single-Phase Rectifier Circuit to Generate High DC Voltage by LC Resonance in Commercial Frequency", *IEEJ Trans. D*, Vol. 127, No. 4, pp. 368-374 (2007) (in Japanese)

[11] I. Yamamoto, K. Matsui, U. Yao: "A Novel Single-Phase Rectifier Circuit with Sinusoidal Input Current with LC resonance in Commercial Frequency", *IEEJ Trans. D*, Vol. 122, No. 8, pp. 838-844 (2002) (in Japanese)

[12] H. Obara, M. Kamaga, T. Ito, Y. Sato: "An Investigation of Capacitors for Flying Capacitor Converters", *IEEJ Trans. D*, Vol. 131, No. 12, pp. 1393-1400 (2011) (in Japanese)

[13] B. J. Baliga, M. Bhatnagar: "Comparison of 6H-SiC, 3C-SiC, and Si for power devices", *IEEE Trans. On Electron Devices*, Vol. 40, No. 3, pp. 645-655 (1993)

[14] M. Bakowski: "Status and Prospects of SiC Power Devices", *IEEJ Trans. D*, Vol. 126, No. 4, pp. 391-399 (2006)