Novel Soft-Switching Active-Bridge Converter for Bi-directional Inductive Power Transfer System

Ryohei Okada∗)  Student Member,  Ryosuke Ota† Member  Nobukazu Hoshi‡ Senior Member

Inductive power transfer (IPT) systems suffer from power loss caused by reactive currents that circulate in the system during soft-switching operation. To address this problem, this paper proposes a novel soft-switching active-bridge (SAB) converter. The SAB converter comprises a full-bridge active (FBA) converter and an LC circuit connected to the one-side leg. This composition suppresses the reactive current circulating between the resonant network and the switching devices. The experiment conducted to compare the proposed converter with a conventional one shows that the efficiency of the IPT system with the SAB converters could be maintained high over a wide operation range. Furthermore, an efficiency improvement by 1.3 pt to the general IPT system could be achieved at 3.3 kW-output.

Keywords: Inductive power transfer (IPT), wireless power transfer (WPT), bi-directional, zero voltage switching (ZVS), soft switching, electric vehicle (EV).

Nomenclature

\(\alpha_1, \alpha_2\) [rad] Phase-shift angles between the legs in the primary/secondary side converters.

\(\delta\) [rad] Phase-shift angle between the gate signals for \(S_{11}\) and \(S_{21}\).

\(I_{SS1, p}, I_{SS2, p}\) [A] \(n\) th-order components of harmonics in \(I_{SS1, p}, I_{SS2, p}\).

\(I_{SS1}, I_{SS2}\) [A] Phasors of \(i_{SS1}, i_{SS2}\).

\(i_1, i_2\) [A] Phasors of \(i_1, i_2\).

\(V_1, V_2\) [V] Phasors of \(v_1, v_2\).

\(\eta\) [%] Efficiency of the whole system.

\(\eta_{\text{max}}\) [%] Maximum value in \(\eta\).

\(\eta_1\) [%] Efficiency of the resonant network.

\(\omega\) [rad/s] Angular frequency of the output voltage in the SAB converter.

\(\phi\) [rad] Phase difference between \(V_1\) and \(V_2\).

\(\theta_0\) [rad] Dead time converted to the angular.

\(C_{SS1}, C_{SS2}\) [F] Representative capacitance for \(C_{SS1}\) and \(C_{SS2}\).

\(C_{SS1}, C_{SS2}\) [F] Capacitances of the DC-blocking capacitors in the primary/secondary sides.

\(C_1, C_2\) [F] Capacitances of the compensation capacitors for the power factor in the primary/secondary side.

\(d\) [mm] Vertical distance between \(L_1\) and \(L_2\).

\(d_{LS}\) [mm] Air gap between the ferrite cores in \(L_{SS}\).

\(E\) [V] DC Voltage at \(E_1 = E_2\).

\(E_1\) [V] DC-supply voltage in the primary side.

\(E_2\) [V] Battery voltage (DC).

\(f\) [Hz] Frequency of the output voltage in the SAB converter.

\(i_{ch11}, i_{ch12}, i_{ch13}\), \(i_{ch14}, i_{ch21}\) [A] Output currents of the primary/secondary side SS-tanks.

\(i_{SS1, SS2}\) [A] Output currents of the primary/secondary side SS-tanks.

\(i_{tr}\) [A] Drain current at turn off switching.

\(k\) Coupling coefficient between \(L_1\) and \(L_2\).

\(L_{SS, max}\) [H] \(L_{SS}\) at maximum efficiency in Fig. 7.

\(L_{SS1}, L_{SS2}\) [H] Inductances of the primary/secondary side SS-coils.

\(L_1, L_2\) [H] Inductances of the transmission coils.

\(M\) [H] Mutual inductance between \(L_1\) and \(L_2\).

\(P_{11}, P_{12}\) [W] Harmonic order.

\(P_{ff}\) [W] Primary/secondary-side conduction losses in the resonant network.

\(P_{\text{res}}\) [W] Total conduction losses in the resonant network.

\(P_{SS, \text{tank}}\) [W] Total conduction losses in the SS tanks.

\(P_{sw, \text{con}}\) [W] Total conduction losses in the SiC-MOSFETs.

\(P_{sw, \text{con1}}, P_{sw, \text{con2}}\) [W] Conduction losses in the primary/secondary-side SiC-MOSFETs.

\(P_{sw, \text{turn off}}\) [W] Total turn-off switching-losses in the converters.

\(P_{\text{tur, off1}}, P_{\text{tur, off2}}\) [W] Functional model of turn-off switching-loss based on the literature (21).

\(P_{\text{tr, max}}\) [W] Maximum rating of \(P_t\) in the experimental system.

\(P_t\) [W] Transmission power.

a) Correspondence to: r. okada@alumni.tus.ac.jp

∗ Department of Electrical Engineering, Faculty of Science and Technology, Tokyo University of Science

2641 Yamazaki, Noda-city, Chiba 278-8510, Japan

© 2020 The Institute of Electrical Engineers of Japan.
Novel Soft-Switching Active-Bridge Converter for Bi-directional Inductive Power Transfer System (Ryohei Okada et al.)

\[ P_\text{tr} [W] \] Rated transmission power.
\[ Q_1, Q_2 \] Quality factors of \( L_1, L_2 \).
\[ r_1, r_2 [\Omega] \] Total ESRs in \( L_1 \) and \( C_1 \), \( L_2 \) and \( C_2 \).
\[ r_{\text{CSS},1,2} [\Omega] \] ESR in \( C_{SS} \) regarding \( n \)-th harmonic component.
\[ r_{\text{LSS},1,2} [\Omega] \] ESR in \( L_{SS} \) regarding \( n \)-th harmonic component.
\[ L_{SS} [\Omega] \] ESR in \( L_{SS} \).
\[ r_{\text{sw},1,2} [\Omega] \] D–S on-resistance of SiC-MOSFETs.
\[ \nu_{\text{CSS}} [V] \] Voltage in \( C_{SS1}, C_{SS2} \).
\[ \nu_{\text{ds}11}, \nu_{\text{ds}12}, \nu_{\text{ds}13}, \nu_{\text{ds}14} [V] \] Drain–source (D–S) voltages in \( S_{11}, S_{12}, S_{13}, S_{14} \).
\[ \nu_{\text{LSS1}}, \nu_{\text{LSS2}} [V] \] Voltages in \( L_{SS1}, L_{SS2} \).
\[ v_1, v_2 [V] \] Output voltages of the primary/secondary side converters.

1. Introduction

These days, many countries promote spreading electric vehicles (EVs) to realize carbon neutrality. However, the driving range per charge is shorter than that of gasoline-powered vehicles. For this, solving the problem is required. Though there is a method to increase the capacity of the battery as the vehicles. For this, solving the problem is required. Though if the switching surge is large, we need to use higher voltage-rating switching-devices. Thus, the cost of the converter goes higher. Hence, it is necessary to reduce the surge voltages and noises.

To address these issues, a soft-switching technique is attracting attention \((16)-(18)\). Especially, in the IPT system shown in Fig. 1(a), soft switching can be realized by using reactive currents generated in the resonant network \((16)-(18)\). However, in a part of the operation range, a large reactive current is needed to realize soft switching. Because of this, the reactive currents flow in the whole system, and then these increase conduction loss \((16)-(18)\). Therefore, it is desirable to improve efficiency with achieving soft switching.

On the other hand, there is also a method where LC circuits are connected to an FBA converter to achieve soft switching \((17)-(19)\). In this method as shown in Fig. 1(b), the reactive current flowing in the resonant network, which has large ESRs, could be reduced because the reactive current is generated by the LC circuit. However, the literature \((17)-(19)\) focuses on only expanding the soft-switching operation-range. Thus, the effect on the power-conversion efficiency by connecting the LC circuits to the converter has not been discussed. In addition, in the converters shown in the literature \((17)-(18)\), the LC circuits are connected to all legs in the converter. This causes increases in the cost and conduction loss.

Therefore, in this paper, to counter these problems, a novel soft-switching active bridge (SAB) converter shown in Fig. 2 is proposed. This proposed SAB converter can provide lower cost and lower conduction-loss than the conventional ones \((17)-(19)\). That is realized by connecting the LC circuit, which is called the soft-switching (SS) tank, to the only one-side leg. Moreover, the effect of the SS tank on the efficiency and the effectiveness of the proposed system are clarified by theoretical analysis and experiments.

This paper is organized in the following. In the next chapter, an overview of the IPT system with the proposed SAB converter is shown. In Chapter 3, the representative operation modes in the SAB converter are described. In addition, in Chapter 4, the soft-switching requirement for the SAB converter is shown. In Chapter 5, the efficiency of the whole system is analyzed. Then, the effect of the design parameters for the SS tank on the efficiency is clarified. In addition, the guideline for the design is shown. Finally, in Chapter 6, the effectiveness of the SAB converter is shown by comparisons with the general IPT system in theoretical analysis and experiments.

![Fig. 1. Concept for the efficient soft-switching IPT system in this paper.](image-url)
In the following, the IPT system comprising the FBA converters is called the “FBA-IPT system”, and the IPT system comprising the SAB converters is called the “SAB-IPT system”.

2. Overview of Proposed SAB-IPT System

2.1 Constitution of SAB-IPT System  The SAB-IPT system comprises the resonant network and the primary- and secondary-side SAB converters shown in Fig. 2. As the resonant network, the series–series topology, where the compensation capacitors $C_1$ and $C_2$ are connected to the transmission coils $L_1$ and $L_2$ in series respectively, is used. Then, $C_1$ and $C_2$ are respectively expressed as

$$C_1 = \frac{1}{\omega^2 L_1}, \quad C_2 = \frac{1}{\omega^2 L_2}. \quad (1)$$

In addition, the SAB converter comprises a general FBA converter and an LC circuit (SS tank). The SS tanks in this system comprise the inductors $L_{SS1}$, $L_{SS2}$, and the capacitors $C_{SS1}$, $C_{SS2}$, respectively. These inductors work to generate reactive currents for soft switching, and these capacitors work to prevent the magnetic asymmetrical phenomenon. In this proposed system, each SS tank is connected to one leg in each SAB converter to reduce a conduction loss. These SAB converters are operated at 85 kHz constantly, and then each output voltage is controlled by phase-shift modulation between the legs in each SAB converter. In the phase-shift modulation, $\alpha_1$ and $\alpha_2$ are controlled respectively. However, the duty ratio control for the legs, in which the current waveforms flowing in both legs are the same, cannot be applied to the SAB converter because the SS tank is connected to only one leg. In addition, the transmission power and the reactive current in the resonant network can be regulated with the phase-shift angle $\delta$ between the primary and secondary sides. The detailed operation of the SAB converter is described in the next chapter.

2.2 Transmission Power in SAB-IPT System  Fig. 3 shows a relationship between the gate signals and each voltage and current in the primary-side SAB converter with soft-switching operation. well as with the FBA converter. In addition, the signs of the voltages and currents in Fig. 3 correspond to the directions of arrows shown in Fig. 2. In regard to $i_{ch11}$, $i_{ch12}$, $i_{ch13}$ and $i_{ch14}$, each positive direction is defined in the direction from the drain pin to the source pin in each SiC-MOSFET. Then, the output voltages $V_1$ in the primary-side SAB converter and $V_2$ in the secondary-side SAB converter can respectively be expressed as

$$V_1 = \frac{2\sqrt{2}E_i}{\pi} \cos \frac{\alpha_1}{2} \cos (\pi + \theta), \quad (2)$$
\[ V_2 = \frac{2\sqrt{2}E_2}{\pi} \cos \frac{a_2}{2} e^{i(\omega t + \frac{\pi}{2} + \phi)}. \]

Here, the resonant network can be analyzed with only the fundamental-frequency component because this resonant network works as a bandpass filter at the resonant frequency. When the ESRs in each element are ignored, the output currents \( I_1 \) and \( I_2 \) in the SAB converters can respectively be expressed as:

\[ I_1 = \frac{2\sqrt{2}E_2}{\pi \omega M} \cos \frac{a_2}{2} e^{i(\omega t + \frac{\pi}{2} + \phi)}, \]
\[ I_2 = \frac{2\sqrt{2}E_2}{\pi \omega M} \cos \frac{a_1}{2} e^{i(\omega t + \frac{\pi}{2} + \phi)}. \]

From the above, the transmission power \( P_t \) can be shown as

\[ P_t = \frac{8E_1E_2}{\pi^2 \omega M} \cos \frac{a_1}{2} \cos \frac{a_2}{2} \cos \phi, \]
\[ \phi = \frac{\pi}{2} - \left( \frac{a_1}{2} - \frac{a_2}{2} + \delta \right). \]

At \( \phi > 0 \), \( P_t \) comes positive, which means the power is transmitted from the primary side to the secondary side. On the other hand, at \( \phi < 0 \), \( P_t \) comes negative. In this paper, the operation at \( \phi > 0 \) is only described because another operation can be described as well.

In addition, in this paper, the efficiency \( \eta_t \) in the resonant network is defined as:

\[ \eta_t = \frac{100P_t}{P_{\text{in}} + r_1|I_1|^2 + r_2|I_2|^2}. \]

Then, the requirement for maximizing \( \eta_t \) is expressed as:

\[ \frac{|V_2|^2}{|V_1|^2} = \frac{|I_1|^2}{|I_2|^2} = \frac{r_2}{r_1}, \]
\[ \phi = 0. \]

Equation (9) shows the requirement in which the power losses between both sides are balanced. On the other hand, \( \phi \) relates to the input and output power-factors in the resonant network, and (10) means the requirement where these power factors become 1. In other words, the reactive current is minimized. Thus, when (9) and (10) are satisfied, the efficiency \( \eta_t \) in the resonant network can be maximized.

### 3. Operation Modes in SAB Converter

In this chapter, the fundamental operation modes in the SAB converter with the soft-switching operation are described. Fig. 4 shows the operation modes in the primary-side SAB converter which correspond to Fig. 3. Since the operation modes in the secondary-side SAB converter can be explained as well as in the primary side, these are not explained. The operation of the SAB converter can be described as divided into the operations of the SS-tank part and the FBA-converter part. The detail for each operation mode is described below.

#### 3.1 Operation Modes in SS tank

The operation modes in the SS tank only depend on the switching in the one-side leg to which the SS tank is connected. For this, the SS tank has two operation modes. In addition, \( C_{SS1} \) works as a DC-blocking capacitor when the average of the voltage \( v_{ds14} \) in one period is not zero. Especially, the average voltage in \( C_{SS1} \) during a period becomes \( E_1/2 \) when the duty ratios of \( S_{13} \) and \( S_{14} \) are set to 0.5. Furthermore, the voltage \( v_{SS} \) can be treated as the constant voltage in each mode when \( C_{SS1} \) is sufficiently large in comparison with \( 1/\omega^2L_{SS1} \), which is the resonant point between \( L_{SS1} \) and \( C_{SS1} \). This design for \( C_{SS1} \) is shown in Chapter 5. Based on the above, the detail for the operation modes of the SS tank is described below.

- \( \theta_{\text{in}} \leq \theta < \theta_{i1} \)
  - \( S_{13} \) turns off, and then \( S_{13} \) and \( S_{14} \) transit into the dead time period. Subsequently, \( S_{13} \) turns on at \( \theta = \theta_{i1} \). Then, \( v_{ds14} \) becomes \( E \). In addition, the voltage in \( C_{SS1} \) is constant at \( E_1/2 \). For this, \( v_{SS} \) becomes \( E_1/2 \). Thus, \( \eta_{SS1} \) varies with \( \Delta v_{SS}/\Delta \theta = E_1/2 \).

- \( \theta_{i1} \leq \theta < \theta_{i4} \), \( \theta_{i3} \leq \theta < \theta_{i4} \)
  - \( S_{13} \) turns off, and then \( S_{13} \) and \( S_{14} \) transit into the dead time period. Subsequently, \( S_{14} \) turns on at \( \theta = \theta_{i4} \). Then, \( v_{ds14} \) becomes 0. In addition, the voltage in \( C_{SS1} \) is constant at \( E_1/2 \). For this, \( \eta_{SS1} \) becomes \( E_1/2 \). Thus, \( \eta_{SS1} \) varies with \( \Delta v_{SS}/\Delta \theta = E_1/2 \).

From the above, the voltages \( v_{SS1}, v_{SS2} \) impressed to \( L_{SS1}, L_{SS2} \) become a square wave as shown in Fig. 3. Moreover, \( v_{SS1} \) and \( v_{SS2} \) flowing in the SS tanks become a triangle wave as shown in Fig. 3.

### 3.2 Operation Modes in FBA Converter

In this section, the operation modes in the FBA converter are described.

- \( \theta_{\text{in}} \leq \theta < \theta_{i1} \)
  - \( S_{12} \) and \( S_{14} \) are ON state. For this, \( v_{ds12}, v_{ds14} \) are 0, and then \( \theta_1 \) becomes 0. Moreover, \( i_{ch12} \) equals \(-i_1\), and \( i_{ch14} \) equals \( i_1 + i_{ss1} \). Then, \( i_{ch11} \) and \( i_{ch13} \) become 0. In addition, \( v_{ds11} \) and \( v_{ds13} \) become \( E \).

- \( \theta_{i1} \leq \theta < \theta_{i4} \)
  - At \( \theta = \theta_{i1} \), \( S_{14} \) turns off, and then \( S_{13} \) and \( S_{14} \) transit into the dead time period. At \( i_1 - i_{ss1} < 0 \), the reverse current flows in \( S_{13} \), and \( v_{ds13} \) becomes 0. Moreover, \( S_{12} \) is ON state. For this, \( v_{ds12} \) is 0, and \( i_{ch12} \) equals \(-i_1 \). Thus, \( v_1 \) becomes \(-E \). Then, \( i_{ch11} \) and \( i_{ch14} \) become 0. In addition, \( v_{ds11} \) and \( v_{ds14} \) become \( E \).

- \( \theta_{i4} \leq \theta < \theta_{\text{in}} \)
  - At \( \theta = \theta_{i4} \), \( S_{13} \) turns on with soft switching because \( v_{ds13} \) is 0 during the switching. Also, \( v_{ds12} \) is 0 because \( S_{12} \) is ON state. Thus, \( v_1 \) becomes \(-E \). Moreover, \( i_{ch12} \) equals \(-i_1 \), and \( i_{ch13} \) equals \( i_1 - i_{ss1} \). Then, \( i_{ch11} \) and \( i_{ch14} \) become 0. In addition, \( v_{ds11} \) and \( v_{ds14} \) become \( E \).

- \( \theta_{\text{in}} \leq \theta < \theta_{i3} \)
  - At \( \theta = \theta_{\text{in}} \), \( S_{11} \) turns off, and then \( S_{11} \) and \( S_{12} \) transit into the dead time period. At \( i_1 < 0 \), the reverse current flows in \( S_{11} \), and \( v_{ds11} \) becomes 0. Moreover, \( S_{13} \) is ON state. For this, \( v_{ds13} \) is 0, and \( i_{ch13} \) equals \(-i_1 - i_{ss1} \). Thus, \( v_1 \) becomes 0. Then, \( i_{ch12} \) and \( i_{ch14} \) become 0. In addition, \( v_{ds12} \) and \( v_{ds14} \) become \( E \).

- \( \theta_{i3} \leq \theta < \theta_{\text{in}} \)
  - At \( \theta = \theta_{i3} \), \( S_{11} \) turns on with soft switching because \( v_{ds11} \) is 0 during the switching. \( v_{ds13} \) is also 0 because \( S_{13} \) is ON state. Thus, \( v_1 \) becomes 0. Moreover, \( i_{ch11} \) equals \( i_1 \), and \( i_{ch13} \) equals \(-i_1 - i_{ss1} \). Then, \( i_{ch12} \) and \( i_{ch14} \) become 0. In addition, \( v_{ds12} \) and \( v_{ds14} \) become \( E \).

As shown in Chapter 5, the design for \( C_{SS1} \) is described in detail. Therefore, the description of the FBA converter is omitted. Of course, the design for \( C_{SS1} \) is shown in Chapter 5. Based on the above, the detail for the operation modes of the SS tank is described below.
At $\theta = \theta_{vi}$, $S_{13}$ turns off, and then $S_{13}$ and $S_{14}$ transit into the dead time period. At $i_1 + i_{SS1} < 0$, the reverse current flows in $S_{14}$, and $v_{ds14}$ becomes 0. $S_{13}$ is ON state. For this, $v_{ds11}$ is 0, and $i_{ch11}$ equals $i_1$. Thus, $v_1$ becomes $E$. Then, $i_{ch12}$ and $i_{ch13}$ become 0. In addition, $v_{ds12}$ and $v_{ds13}$ become $E$.

- $\theta_{vi} \leq \theta < \theta_{ui}$

At $\theta = \theta_{vi}$, $S_{14}$ turns on with soft switching because $v_{ds14}$ is 0 during the switching. Also, $v_{ds11}$ is 0 because $S_{11}$ is ON state. Thus, $v_1$ becomes $E$. Moreover, $i_{ch11}$ equals $i_1$, and $i_{ch14}$ equals $i_1 + i_{SS1}$. Then, $i_{ch12}$ and $i_{ch13}$ become 0. In addition, $v_{ds12}$ and $v_{ds13}$ become $E$.

- $\theta_{ui} \leq \theta < \theta_{u}$

At $\theta = \theta_{ui}$, $S_{11}$ turns off, and then $S_{11}$ and $S_{12}$ transit into the dead time period. At $-i_1 < 0$, the reverse current flows in $S_{12}$, and $v_{ds12}$ becomes 0. $S_{14}$ is ON state. For this, $v_{ds14}$ is 0, and $i_{ch14}$ equals $i_1 + i_{SS1}$. Thus, $v_1$ becomes 0. Then, $i_{ch11}$ and $i_{ch12}$ become 0. In addition, $v_{ds11}$ and $v_{ds13}$ become $E$.

4. Soft-Switching Requirement for SAB Converter

In this chapter, the soft-switching requirement for SAB converter and the method how to achieve soft switching are described. The soft switching is divided into soft-switching turn-off and -on. When the switching device is turned off, the parasitic D–S capacitance works so as to prevent the rapid voltage rising \cite{5}. Therefore, in this paper, it is assumed that the soft-switching turn-off is always achieved. For this, unless otherwise noted, “soft-switching turn-on” is simply called “soft switching” in the following.

Soft switching can be achieved by making the D–S voltage zero before turning the switching device on. In order to make the D–S voltage zero, it is necessary to pass a reverse current into the switching device and discharge the charge stored in the D–S capacitance. In the SAB converter, soft switching can be achieved by generating reactive current in the SS tank and using that current as the reverse current. Based on the previous chapter, the soft-switching requirement for all switching devices can be expressed as

$$
\begin{align}
  &i_1 \left(-\frac{\alpha_1}{2}\right) \leq 0 \\
  &i_1 \left(\frac{\alpha_1}{2}\right) \leq 0 \\
  &i_1 \left(\alpha_1 - \frac{\alpha_2}{2}\right) + i_{SS1} \left(\alpha_1 - \frac{\alpha_2}{2}\right) \leq 0 \\
  &i_1 \left(\alpha_1 + \frac{\alpha_2}{2}\right) + i_{SS1} \left(\alpha_1 + \frac{\alpha_2}{2}\right) \leq 0, \\
  &i_2 \left(-\delta + \alpha_2 - \frac{\alpha_1}{2}\right) \geq 0 \\
  &i_2 \left(-\delta + \alpha_2 + \frac{\alpha_1}{2}\right) \geq 0 \\
  &i_2 \left(-\delta - \frac{\alpha_1}{2}\right) + i_{SS2} \left(-\delta - \frac{\alpha_1}{2}\right) \geq 0 \\
  &i_2 \left(-\delta - \frac{\alpha_1}{2}\right) + i_{SS2} \left(-\delta + \frac{\alpha_1}{2}\right) \geq 0,
\end{align}
$$

where $i_{SS1}$ and $i_{SS2}$ can respectively be approximated below.

$$
\begin{align}
  i_{SS1} &\approx \sum_{n=1}^{5} \frac{2\pi E_1 \sin \frac{\alpha_1}{2} \sin \left[n \left(\theta - \alpha_1 + \frac{\alpha_2}{2} - \frac{\alpha_1}{2}\right)\right]}{\omega L_{S11} \left(\frac{\alpha_1}{2}\right)^2}, \\
  i_{SS2} &\approx \sum_{n=1}^{5} \frac{2\pi E_2 \sin \frac{\alpha_1}{2} \sin \left[n \left(\theta + \delta + \frac{\alpha_1}{2} + \frac{\alpha_1}{2}\right)\right]}{\omega L_{S12} \left(\frac{\alpha_1}{2}\right)^2}.
\end{align}
$$

The formula (11) shows the soft-switching requirement in the primary-side. On the other hand, (12) means the soft-switching requirement in the secondary-side. From (11) and (12), we can understand that $i_{SS1}$ and $i_{SS2}$ are added to the soft-switching requirement shown in the literature\cite{15,16}, which is for the general FBA-IPT system. In other words, the reactive current circulating between the resonant network and all switching devices can be reduced because $i_{SS1}$ and $i_{SS2}$ are added to the soft-switching requirement.


5. Theoretical Analysis of SAB-IPT System

In order to furthermore improve the system efficiency, it is necessary to design the SS tank as shown in the previous chapter. Considering a balance of these losses caused by \( i_{SS1} \), \( i_{SS2} \), \( i_1 \), and \( i_2 \) is important. Especially, the currents \( i_{SS1} \) and \( i_{SS2} \) can be designed with \( L_{SS1} \) and \( L_{SS2} \). This chapter clarifies the efficiency characteristic of the whole system versus the variations of \( L_{SS1} \), \( L_{SS2} \). And then, the design guideline for the SS tank is shown. However, in this analysis, the input and output voltages \( E_1 \) and \( E_2 \) are constant. In addition, it is assumed that \( L_{SS} = L_{SS1} = L_{SS2} \).

### 5.1 Analysis Model of SS Tank

In actual inductors, ESR in \( L_{SS} \) changes with the change of the inductance \( L_{SS} \). To counter this, in this section, a power loss model for \( L_{SS} \) based on the measurement is designed. And then, the efficiency of the whole system is analyzed with this model.

Fig. 5 shows an appearance of \( L_{SS} \). In addition, Table 1 shows the \( L_{SS} \) specification, which includes the Litz wire and the ferrite core. In this paper, for simplicity, \( L_{SS} \) is adjusted by changing not the number of turns but the gap \( d_{SS} \).

![Fig. 5. Appearance of \( L_{SS} \) in the experimental system.](image)

By changing the gap \( d_{SS} \), the variation of \( L_{SS} \) regarding the soft-switching operation range is discussed in Chapter 6 with the system efficiency. Furthermore, the larger \( L_{SS1} \) and \( L_{SS2} \) come, the higher freedom degrees of \( i_1 \) and \( i_2 \) come. By this, the soft-switching operation range which satisfies (10) is spread. The detail regarding the soft-switching operation range is discussed in Chapter 6 with the system efficiency. Therefore, it is necessary to appropriately design so as to get a balance between them. In the next chapter, the guideline for the design is shown.

### Table 1. Specification of the inductor \( L_{SS} \)

| Product source | Isolcon Magnet Wire Works Ltd |
|----------------|-------------------------------|
| Diameter       | 5 mm                          |
| Number of turns| 13                            |
| Litz wire      |                               |
| Ferrite core   |                               |
| Model number   | PC40 EC120X101X30             |
| Air gap \( d_{SS} \) | 3 – 18 mm                  |

![Table 2. Circuit parameters in the experimental system](image)

| \( P_{in,pw} \) | 3.3 kW            |
| \( E_1, E_2 \) | 230 V             |
| \( f \)          | 85 kHz            |
| \( \theta_2 \)    | 0.214 rad (400 ns) |
| \( E_1, L_2 \)   | 62.1, 69.0 \( \mu \)H |
| \( C_1, C_2 \)   | 55.5, 48.6 nF     |
| \( L_{SS1}, L_{SS2} \) | 20.0 \( \mu \)H |
| \( C_{SS1}, C_{SS2} \) | 20.0 \( \mu \)F |
| \( r_1, r_2 \)   | 128.0 (\( Q_1 = 259 \)), 144.0 (\( Q_2 = 256 \)) \( \Omega \) |
| \( r_{CSS1}, r_{CSS2}, r_{CSS3} \) | 3.5, 4.7, 5.5 \( \Omega \) |
| \( r_{SS1}, r_{SS2} \) | 3.2 \( \Omega \), 0.9 \( \Omega \) |
| \( r_{SS3} \)    | 5.9 \( \Omega \), 0.8 \( \Omega \) |
| \( r_{SS4} \)    | 25 1\( \Omega \)  – 113.2 \( \Omega \) |

### Table 3. Formulas for the power loss models

| Calculation formula                                                                 |
|-------------------------------------------------------------------------------------|
| \( P_{in,pw} \) \( r_1 \) \( I_1^2 \) \+ \( r_2 \) \( I_2^2 \) \+ \( \epsilon_{LSS} \) \( \frac{d}{dt} \left( E_1 I_1 + E_2 I_2 \right) \) \+ \( \epsilon_{CSS} \) \( \frac{d}{dt} \left( E_1 I_1 + E_2 I_2 \right) \) \+ \( \epsilon_{CSS} \) \( \frac{d}{dt} \left( E_1 I_1 + E_2 I_2 \right) \) |
| \( P_{sw,con} \) \( r_{CSS1} + r_{CSS2} + I_{CSS3} \left( |E_1|^2 + |E_2|^2 \right) \) \+ \( r_{CSS1} + r_{CSS2} + I_{CSS3} \left( |E_1|^2 + |E_2|^2 \right) \) \+ \( r_{CSS1} + r_{CSS2} + I_{CSS3} \left( |E_1|^2 + |E_2|^2 \right) \) |
| \( P_{CSS} \) \( \sum \left( \left( r_{SS1} + r_{SS2} + I_{CSS3} \right) \left( |E_1|^2 + |E_2|^2 \right) \right) \) |
| \( P_{sw,turn off} \) 0.023 \( \frac{d}{dt} \left( E_1 |I_1| + E_2 |I_2| \right) – 0.104 \( \frac{d}{dt} \left( E_1 |I_1| + E_2 |I_2| \right) – 0.607 \) |

Each power-loss model is defined in Table 3. In regard to \( P_{sw,turn off} \), it is known that non-negligible switching-loss is occurred even with soft-switching turn-off, which depends.
on the current at the turn-off. For this, \( P_{\text{on,turn off}} \) is calculated from a function \( P_{\text{on,turn off}}(t_0, \text{turn off}) \), which is shown in Table 3 and modeled based on the datasheet of the switching device. On the other hand, the conduction loss during the dead time \( \theta_d \) is ignored because the ratio of \( \theta_d \) occupied in the operation period is small. In addition, the circuit parameters used in the analysis are based on the actual measurement or the datasheet shown in Table 2.

### 5.3 Design of \( L_{SS} \)

Fig. 7 shows the theoretical maximum-efficiency \( \eta_{\text{max}}(L_{SS}) \) characteristics of the whole system at \( P_u = 3.3 \text{ kW} \) when \( L_{SS} \) is varied. Each plot point of \( \eta_{\text{max}}(L_{SS}) \) is exhaustively explored from sets including the control parameters \( \alpha_1, \alpha_2 \) and \( \phi \) which satisfy

\[
\cos \frac{\alpha_1}{2} \cos \frac{\alpha_2}{2} \cos \phi = \frac{\pi^2 \omega M}{8E_1E_2} P_u.
\]

(16)

In addition, from Fig. 7, it is confirmed that the characteristics of \( \eta_{\text{max}}(L_{SS}) \) also vary according to the variation of the coupling between transmission coils, which is represented as coupling coefficient \( k \). Moreover, we can confirm the inductance \( L_{SS,\text{max}} \), which maximizes \( \eta_{\text{max}} \), also varies according to \( k \). At the maximum point \( \eta_{\text{max}}(L_{SS,\text{max}}) \), the equal signs in (10), (11), and (12) are satisfied. In other words, at these operation points, the soft-switching requirement is achieved by keeping the currents in the resonant network and the SS tanks minimum. Furthermore, as shown in Fig. 7, the smaller \( k \) is, the smaller \( L_{SS,\text{max}} \) comes.

In the series/series resonant-network topology, the smaller \( k \) is, the larger the transmission power \( P_u \) comes. For this, in order to keep \( P_u \) constant, the phase-shift angles \( \alpha_1, \alpha_2 \) between the legs need to be increased, and then \( V_1, V_2 \) have to be small. In this case, the quantities of the currents \( i_1(\alpha_1 - \theta_d/2), i_2(\alpha_1 + \theta_d/2) \) and \( i_2(-\delta + \theta_d/2) \), which flow in the resonant network at the timing of the turn-on switching, increase. Thus, the required quantity of the reactive current to achieve soft switching also goes large. Therefore, when \( k \) is small, it is necessary to decrease the inductance \( L_{SS} \) in order to achieve soft switching with satisfying (10), (11), and (12).

In this paper, \( L_{SS} \) is designed with 20.0 \( \mu \text{H} \) where the efficiency comes maximum at the maximum coupling \( k = 0.30 \). In actual applications, the efficiency can be optimized by designing \( L_{SS} \) with considering overall power-charging cycle. However, this advanced design method is not discussed in this paper but will be discussed in future work.

### 5.4 Design of \( C_{SS1} \) and \( C_{SS2} \)

As shown in Chapter 3, \( C_{SS1} \) and \( C_{SS2} \) are respectively connected to \( L_{SS1} \) and \( L_{SS2} \) in series to prevent a magnetic asymmetrical phenomenon. Then, it is necessary to restrain them from resonating and \( v_{CSS} \) from oscillating. For this, we need to design the capacitors \( C_{SS1} \) and \( C_{SS2} \) so that these capacitances are sufficiently large.

Here, \( v_{CSS} \) can be expressed as

\[
v_{CSS} = \frac{E_1}{2} + \sum_{n=1}^{\infty} \frac{2E_1}{nn(1-n\pi^2L_{SS}C_{SS})} \sin n\omega t,
\]

(17)

where \( C_{SS} = C_{SS1} = C_{SS2}, E = E_1 = E_2 \) and the phase delay is ignored for simplicity. From (17), the distortion ratio of the fundamental wave component to the DC component can be expressed as

\[
\text{Distortion ratio [%]} = \frac{2\sqrt{2}}{\pi|1 - \omega^2L_{SS}C_{SS}|} \times 100.
\]

In this paper, \( C_{SS} \) is designed so that the distortion ratio becomes \( 1 \% \) or less.

The circuit parameters of the SS tank shown in Table 2 are designed based on the above design guideline. In the next chapter, the effectiveness of the SAB converter is shown by analysis and experiments.

### 6. Comparison with Proposed SAB-IPT System and Conventional FBA-IPT System

In this chapter, the effectiveness of the proposed SAB-IPT system is clarified by comparison with the FBA-IPT system. First, the FBA-IPT and SAB-IPT systems in soft-switching operation are compared regarding the power-loss-analysis results. Next, influences of the SS tank on the whole-system efficiency are discussed. Finally, by experiments, the validity of each analytical result and the effectiveness of the SAB-IPT system are shown.

#### 6.1 Analytical and Experimental Conditions

In these analyzes and experiments, the circuit parameters shown in Table 2 are used. In addition, the FBA-IPT system is controlled with the method shown in the literature (15) so as to be high efficiency under soft-switching operation. On the other hand, the SAB-IPT system is controlled with the high-efficiency points derived in the previous chapter. Furthermore, the primary- and secondary-sides converters are synchronized and controlled with one FPGA controller. In addition, each system is controlled with open-loop according to the table of the operation points.

Here, Fig. 8 shows the appearance of the experimental system. In this experiment, the coupling coefficient \( k \) is adjusted by changing only the vertical distance \( d \) between the coils. However, the horizontal position is not adjusted.

#### 6.2 Comparison with Theoretical Analysis

Fig. 9 shows the theoretical overall efficiency in the soft-switching operation range at \( k = 0.20 \). From Fig. 9, we can confirm that the SAB-IPT system can achieve soft switching over a wide operation range in comparison with the FBA-IPT system. As a result, the SAB-IPT system can be operated close...
to the high-efficiency condition (10) over a wide range. Here, in Fig. 9, the dashed line represents the maximum efficiency of each transmission power. Therefore, the FBA-IPT and the SAB-IPT systems can be operated with high efficiency by controlling them based on each dashed line.

Fig. 9. The theoretical overall efficiency in the soft-switching operation range \((k = 0.20)\).

Fig. 10 shows the theoretical power losses in the FBA-IPT and SAB-IPT systems under the soft-switching operation at \(k = 0.20\) and \(P_n = 3.3\ kW\). However, each power loss is calculated according to Table 3. From Fig. 10, we can confirm that the power loss in the resonant network of the SAB-IPT system is reduced in comparison with that of the FBA-IPT system. This reason is that, in the SAB-IPT system, most of the reactive current does not flow in the resonant network but the SS tank. Furthermore, the power losses in the converters can also be reduced. This means that connecting the SS tank to only one leg contributes to the improvement. However, the power losses in the SS tanks are very small in comparison with other losses. In this case, the current in the SS tank is small in comparison with that in the resonant network, where \(|I_1| = 21.0\ A\) and \(|I_{ss1}| = 9.8\ A\). In addition, the ESR in the SS tank is very small. As a result, the power loss in the SS tanks becomes very small in comparison with other losses.

On the other hand, in the FBA-IPT system, the power losses in the converters end up increasing because the reactive current generated in the resonant network flows in both legs. As a result, the power losses in the whole system can be reduced, and then the efficiency can be improved by using the SAB-IPT system. In the next section, the effectiveness is also confirmed by the experiment.

6.3 Comparison with Experiment

In this section, the following two items are confirmed by the experiment.

- Validity of the analysis result for the SAB-IPT system efficiency in regard to the design of the SS tanks.
- Validity of the comparison result between the SAB-IPT and FBA-IPT systems by the theoretical analysis.

6.3.1 Comparison between Results in Analysis and Experiment

Fig. 11 shows the relationship between the overall efficiency and \(L_{ss}\) in the experimental system at \(P_n = 3.3\ kW\). From Fig. 11, we can confirm that the tendency of the experimental results agrees with that of the theoretical analysis results. The difference between them was small when \(L_{ss} > 20.0\ \mu\) H, though the maximum efficiency at \(k = 0.30\) could not be confirmed within the measured range. It can be said that this efficiency analysis sufficiently has validity regarding the design of the SS tanks.
6.3.2 Efficiency and Power Loss in SAB-IPT and FBA-IPT Systems First, the achievement of soft switching in each system is confirmed from the waveforms. The converters in each experimental system are composed of 2-in-1 modules. Therefore, it is difficult to measure the drain current directly. For this reason, we judged that soft switching was achieved from the output waveforms in the converter, which satisfy the soft-switching requirement in (11) and (12), by comparing them with the hard-switching waveforms. Fig. 12(a) shows the output waveforms in the FBA-IPT system. From Fig. 12(a), $t_1$ and $t_2$ satisfy the soft-switching requirement shown in (11) and (12). Furthermore, the achievement of soft switching can be confirmed from the voltage waveforms at turn on.

Next, Figs. 12(b) and 12(c) show the output waveforms in the SAB-IPT system. Fig. 12(b) represents the waveforms on the primary side. Fig. 12(c) represents the waveforms on the secondary side. From Figs. 12(b) and 12(c), $t_{\text{SS}1}$ and $t_{\text{SS}2}$ satisfy the soft-switching requirement shown in (11) and (12), respectively. We can confirm the achievement of soft switching from the voltage waveforms at the turn-on.

Here, Fig. 13 shows the overall efficiencies in the FBA-IPT and SAB-IPT systems. In Fig. 13, the efficiency of the FBA-IPT system significantly decreases in the low power range, though the efficiency in the high power range is high. On the other hand, in comparison with the FBA-IPT system, the efficiency of the SAB-IPT system can be maintained high regardless of the operation range. In the low power range, the phase-shift angles $\alpha_1$ and $\alpha_2$ need to be large to suppress the transmission power $P_{\text{tr}}$. In other words, the reactive current required for soft switching also increases. Therefore, the effectiveness of the SAB-IPT system with the SS-tank assistance stands out. On the other hand, in the high power range, the SAB-IPT system also has effectiveness, though the SS tank does not work very effectively because a large reactive current is not required for soft switching. Especially, an efficiency improvement by 1.3 pt can be achieved at $P_{\text{tr}} = 3.3$ kW ($k = 0.20$). Furthermore, an efficiency improvement by 4.3 pt can be achieved at $P_{\text{tr}} = 1.3$ kW ($k = 0.20$).

Fig. 13 shows that the efficiency of the FBA-IPT system is higher than that of the SAB-IPT system by 0.08 pt when $P_{\text{tr}} = 3.3$ kW and $k = 0.30$. In the FBA-IPT system, the phase-shift angles $\alpha_1$ and $\alpha_2$ are small, and the reactive current for soft switching is also small at $P_{\text{tr}} = 3.3$ kW and $k = 0.30$. In this case, the influence of the power loss in the SS tanks cannot be negligible. That is why the efficiency of the FBA-IPT system is slightly higher than that of the SAB-IPT system.
IPT systems suffer from the power loss caused by the reactive current during soft-switching operation. To address this, a novel SAB converter was proposed in this paper. The proposed SAB converter comprises a general FBA converter and an SS tank connected to only the one-side leg in the FBA converter. By this composition, this SAB-IPT system can reduce the reactive current circulating in the system and achieve higher efficiency. The effectiveness of the prosed system was clarified as shown in the following:

1. The structure of the SAB converter and its operation modes were shown.
2. The soft-switching requirement in the SAB-IPT system was discussed. In addition, based on theoretical analysis, the SS tanks were designed so as to improve the efficiency at the maximum coupling between the transmission coils.
3. The proposed SAB-IPT system was compared with the FBA-IPT system based on the theoretical analysis and the experiments.

The theoretical analysis confirmed that connecting the designed SS tanks to the converters could significantly suppress the conduction loss caused by the reactive current. As a result, the overall efficiency of the SAB-IPT system got higher than that of the FBA-IPT system. The efficiency improvement was also confirmed in the experiments. These experimental results had a good agreement with the results derived in the theoretical analysis. In addition, the efficiency improvement by the SAB-IPT system was confirmed over a wide operation range. Especially, an efficiency improvement by 1.3 pt could be achieved at $P_{tr} = 3.3 \text{ kW (k = 0.20)}$. Furthermore, an efficiency improvement by 4.3 pt could also be achieved at $P_{tr} = 1.3 \text{ kW (k = 0.20)}$.

In future works, the proposed SAB converter will be applied to other resonant network topologies, and then the effectiveness will be discussed. In addition, to furthermore improve efficiency, a design method which considers behavior as a battery charger is also discussed.

Acknowledgment

This work is supported by JSPS KAKENHI Grant Number 20K14723 and Tokyo University of Science.

References

(1) X. Ge, Y. Sun, Z. Wang, C. Tang: “Dual-independent-output inverter for dynamic wireless power transfer system”, IEEE Access, Vol.7, pp.107320–107333 (2019)
(2) J. Zhao, T. Cai, S. Duan, H. Feng, C. Chen, X. Zhang: “A general design method of primary compensation network for dynamic wpt system maintaining stable transmission power”, IEEE Transactions on Power Electronics, Vol.31, No.12, pp.8343–8358 (2016)
(3) T. Fujita, T. Yasuda, H. Akagi: “A dynamic wireless power transfer system applicable to a stationary system”, IEEE Transactions on Industry Applications, Vol.53, No.4, pp.3748–3757 (2017)
(4) J. Zhang, Z. He, A. Luo, Y. Liu, G. Hu, X. Feng, L. Wang: “Total harmonic distortion and output current optimization method of inductive power transfer system for power loss reduction”, IEEE Access, Vol.8, pp.4724–4736 (2020)
(5) X. Qu, Y. Jing, H. Han, S. Wong, C. K. Tse: “Higher order compensation for...
Novel Soft-Switching Active-Bridge Converter for Bi-directional Inductive Power Transfer System (Ryohei Okada et al.)

Ryohei Okada (Student Member) was born in Kanagawa, Japan, in June. 1996. He received a B.S. degree in Electrical Engineering from Tokyo University of Science, Japan in 2020. He is currently a second-year M.S. student in the university. His research interests include power electronics, wireless power transfer and electric vehicles. He is a student member of IEEJ and a student member of the IEEE.

Ryouke Ota (Member) was born in Nagano, Japan, in Sept. 1991. He received a B.S., M.S. and Ph. D. degree in Electrical Engineering from Tokyo University of Science, Japan in 2014, 2016 and 2019, respectively. During his PhD, he was working on Inc. KADOKAWA as a Novel Editor in 2016 - 2018. He was also a Research Fellow of the Japan Society for the Promotion of Science (JSPS) in 2018 – 2020. After his PhD., He stayed The University of Auckland in New Zealand as a Visiting Researcher in 2019 and 2020. He is currently working on Tokyo University of Science, Japan as an assistant professor. His interests include power electronics, wireless power transfer and DC-DC converter etc. He is a member of IEEE, a member of IEICE and a member of the IEEE. He has a 2020 IEEE PELS WoW Best Paper Award from IEEE, a Young Engineer Presentation Award in 2020 from IEICE, 2014 IEEJ Industry Applications Society Excellent Presentation Award in 2014 from IEEJ and 17th ICEMS Best Paper Award at 2014 from IEEE.

Nobukazu Hoshi (Senior Member) was born in Kanagawa, Japan, in 1969. He received the B.S., M.S., and Ph.D. degrees from Yokohama National University, Yokohama, Japan, in 1992, 1994, and 1997, respectively, all in electrical engineering. From 1994 to 1997, he was a Research Fellow of the Japan Society for the Promotion of Science. In 1997, he joined the Department of Electrical and Electronic Engineering, Ibaraki University, Hitachi, Japan, as a Research Associate and became an Assistant Professor in 2005. From 2008 to 2014, he was an Associate Professor and is currently a Professor in the Department of Electrical Engineering, Faculty of Science and Technology, Tokyo University of Science, Noda, Japan. His research interests include power electronics, motor control, electric vehicles, and hydrogen generation systems. Dr. Hoshi is a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE), a member of the Japan Institute of Power Electronics, the Society of Automotive Engineers of Japan, and the Japan Society of Applied Electromagnetics and Machines. He was a co-recipient of IEEE IAS Committee Prize Paper Award in 1998 and 2010 and IEEJ Industry Applications Society Paper Award in 2013.