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Analysis and Elimination of Dead-Time Effect in Wireless Power Transfer System

Xin Liu ¹ , Tianfeng Wang ¹, Nan Jin ^{2,*}, Salman Habib ¹, Muhammad Ali ¹, Xijun Yang ^{1,*} and Houjun Tang ¹

¹ Key Laboratory of Control of Power Transmission and Transformation Ministry of Education, Shanghai Jiao Tong University, 800 Dongchuan RD., Shanghai 200240, China; Liu_xin@sjtu.edu.cn (X.L.); wangtf1992@163.com (T.W.); salmanhabib560@gmail.com (S.H.); engrmak.ee@sjtu.edu.cn (M.A.); hjtang@sjtu.edu.cn (H.T.)

² College of Electric and Information Engineering, Zhengzhou University of Light Industry, Zhengzhou 450002, China

* Correspondence: jinnan@zzuli.edu.cn (N.J.); yangxijun@sjtu.edu.cn (X.Y.); Tel.: +86-151-3713-6129 (N.J.); +86-138-1606-6208 (X.Y.)

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Abstract: Dead time between the complementary driving signals is needed to avoid short circuit in voltage source inverters (VSIs), however, this raises issues such as voltage distortion and harmonic generation. In wireless power transfer (WPT) systems, the ratio of dead time versus operating period becomes more problematic due to the high frequency, where the dead time can cause serious concerns regarding the phase errors and control performance deterioration. Therefore, this paper presents a comprehensive analysis of the dead-time effect for WPT systems based on a series-series (SS) topology. Firstly, it is found that voltage distortion appears in two regions in comparison with the three in one active bridge WPT system, and seven regions, as compared to the eight in dual active bridge (DAB) WPT system. Afterwards, a novel pulse width modulation (PWM) method is proposed, where the driving signals of the same phase leg are no longer complementary to each other. By employing the proposed method, the dead-time effect can be addressed up to a certain extent, and the desired voltage can be obtained in all the regions. In addition, the proposed method is not influenced by the system parameters, and can be easily applied to other high-frequency resonant converters. Simulated and experimental results are added to verify the feasibility and efficacy of the proposed control scheme.

Keywords: dead-time effect; dead-time elimination; dual active bridges (DAB); phase control (PC); wireless power transfer (WPT)

1. Introduction

Wireless power transfer (WPT) system can realize the power conversion by coupling coils through a magnetic field. The air gap between the coils can range from a few millimeters to several meters, the operating frequency from kHz to MHz, and the power level from mW to MW. WPT technique has experienced a great development in the last decade, due to its merits of convenience and safety. Many researches have been implemented, including magnetic material design [1], coil optimization [2], power management [3,4], etc. In addition, WPT technology has been applied to various applications, such as communication networks, biomedical implants, consumer electronics, and electric vehicles [3–8].

The active bridge topology is widely utilized to overcome the problems in the traditional diode rectifier for various power converters. Recently, dual active bridge (DAB) WPT systems are highly acclaimed. Active bridges in the WPT systems can function as a voltage regulator and contribute to the

reduction of conduction losses, load transformation, and bidirectional power transfer. In [9], forward voltage losses of the diodes are eliminated by a synchronous rectifier. In [10], dual-side phase control regulates the primary and secondary resonant currents, which can further reduce the losses consumed by the parasitic resistances. In [11–14], secondary phase control is applied to transform the load and eliminate the reactance caused by the detuning of the WPT system. The active bridges can effectively contribute toward maintaining the high power transfer efficiency against large variations of the load and the power transfer distance. In [15–17], two active bridges realize the bidirectional wireless power transfer by controlling three phase angles, providing energy connection between the battery and the grid. In order to avoid short circuit, dead time should be inserted into the complementary driving signals in the voltage source inverters (VSIs). However, the influence of the dead time of the DAB WPT systems becomes more complex, due to the utilization of two VSIs.

During the dead time, both the upper and lower side switches in a VSI phase leg are off, and the current freewheels through the diode. However, such a blanking period can affect the reliability, power quality and losses of the system [18]. In the high-frequency WPT systems, the ratio of the dead time versus operating period becomes more significant, and dead-time effect can cause issues, such as voltage distortion, phase errors, harmonic generation, and control performance deterioration. In a study [19], voltage distortion is observed. The square-wave voltage reverses polarity many times within a short time, which causes additional switching losses and may destroy the semiconductor devices. In [10], it is reported that the transferred power of the WPT system is a sine function of the phase angles. However, the dead-time effect can bring about concerns regarding the phase errors, and the transferred power will be affected. In [11–14], secondary phase angles of the DAB WPT systems are used to realize maximum efficiency point tracking. The phase errors caused by the dead time deteriorates the control performance and will affect the power transfer efficiency. In addition, the dead time can generate undesired harmonics, which may cause electromagnetic interference (EMI) problems.

Methods describing the issues of dead time can be classified into three categories: dead-time effect minimization, dead-time compensation, and dead-time elimination. In [18], an adaptive dead-time regulation method is proposed based on a buck converter to minimize the dead-time effect. However, minimization methods cannot completely remove the dead-time effect [20,21]. Compensation methods require accurate current sensing and a complex algorithm, and the performance heavily depends on the system parameters [22,23]. Thus, the dead-time elimination method becomes more promising. In [24–26], the lower-side switch of a phase leg remains off during the positive half cycle of the current, whereas the upper-side switch remains off during the negative half cycle. Since the switches are no longer complementary to each other, the dead time is not necessary. All the aforementioned methods have been applied to the grid-tied inverters, where the frequency of the output current is much lower than the switching frequency. However, the current frequency of the resonant systems is identical to the switching frequency, and the current polarity detection required by the dead-time elimination becomes more difficult. The conventional dead-time elimination method cannot be applied to the WPT systems. Although the optimal dead time value for the primary active bridge of a double-side inductor–capacitor–capacitor (LCC) WPT system has been deduced in [19], however, only one condition of the dead-time effect is investigated, and more issues regarding dead time are yet to be explored. Detailed analysis and elimination methods of the dead-time effect in the WPT systems are scarcely discussed in the literature.

This paper presents a comprehensive analysis of the dead-time effect that may occur in the WPT systems based on a series-series (SS) topology. By employing proper utilization of freewheeling diodes, part of the driving signals can be turned off in advance. Based on this characteristic, a novel dead-time elimination method is proposed in the DAB WPT system whose dead-time effect should be the most complex. This paper has the following significant merits: Firstly, the proposed technique provides suitable guidelines for control signal configuration of WPT systems and effectively contributes in producing the desired voltage without phase errors in all operating regions of the WPT systems, which further leads to the realization of flexible power conversion. Secondly, the proposed technique is not influenced by the system

parameters, which makes its application easier for other resonant VSIs. Finally, it can support to increase the operating frequency of the system even using the same semiconductor devices.

This paper is organized as follows. Section 2 analyzes the dead-time effect of the WPT systems. Section 3 presents the theoretical basis of the dead-time elimination of the DAB WPT system at first, followed by a novel pulse width modulation (PWM) method proposed to address the significant issues of the dead time. In Section 4, the simulations and experiments are elaborated. Finally, the conclusion is drawn in Section 5.

2. Modeling of WPT System

The schematic of the SS DAB WPT system is shown in Figure 1a. Since the SS topology consists of few resonant devices, it can reduce the cost, volume, and weight of the resonant network, which makes it widely adopted. $V_{1,dc}$ and $V_{2,dc}$ are the DC voltage sources. C_0 and C_3 are the filtering capacitors, whereas C_1 and C_2 are the primary and secondary compensation capacitors. Q_1 – Q_8 are the MOSFETs, and D_1 – D_8 are the diodes. The primary and secondary resonant voltages and currents are denoted as v_1 , v_2 , i_1 , and i_2 , respectively. The power can be transferred in both directions by controlling the phase difference between v_1 and v_2 . L_1 and L_2 are the inductances of the transmitting and receiving coils whose parasitic resistances are R_1 and R_2 , respectively.

According to the fundamental harmonic analysis and the circuit theory, the current loops of the primary and secondary sides can be obtained.

$$v_1 = i_1(R_1 + j\omega L_1 + \frac{1}{j\omega C_1}) + j\omega M i_2 \quad (1)$$

$$v_2 = i_2(R_2 + j\omega L_2 + \frac{1}{j\omega C_2}) + j\omega M i_1 \quad (2)$$

The ideal waveforms of the active bridge in the WPT system with zero dead time are shown in Figure 1b [13,15]. The phase angle of v_2 is denoted as 2β , and v_2 leads i_2 by ϕ which can range from 0 to 360° in the DAB WPT system. The driving signals of the same phase leg are complementary to each other. Therefore, the dead time should be inserted to avoid short circuit in the experiments. However, the dead time can bring about some adverse effects. The following parts clearly elaborate the dead-time effect that may occur in the WPT systems.

Figure 1. Dual active bridge (DAB) wireless power transfer (WPT) system. (a) System schematic; (b) Ideal waveforms with zero dead time.

2.1. Dead-Time Effect of One Active Bridge WPT System

Primary active bridge and secondary diode bridge are adopted in most WPT systems, that is, only four diodes are used on the receiver side. The power is regulated by DC–DC converters, and the primary active bridge only functions as DC–AC conversion. The transmitter operates near the resonant point for high efficiency. Thus, there exist three operating modes of the primary active bridge. Figure 2 shows the three kinds of typical waveforms of the one active bridge WPT system with dead time T_d , including the driving signals, the actual voltage and current, the desired voltage and the corresponding error waveform. θ_d corresponds to the phase angle during the dead time and 2γ presents the phase angle of the error waveform. The rising edge of the driving signal is delayed in order to obtain the required dead time, and v_1 is expected to change when the driving signal is turned off. In Figure 2a, θ_d is inserted when i_1 is positive. v_1 becomes positive until Q_1 is turned on, and it becomes negative until Q_2 is turned on. The left part of v_1 is missing, whereas the right part of v_1 is extended. It is equivalent to shift v_1 right by θ_d . In Figure 2b, θ_d is inserted during the zero-crossing point of i_1 . An error negative pulse and then an error positive pulse are produced, which has been observed in [19]. In Figure 2c, θ_d is inserted when i_1 is negative. v_1 becomes positive as soon as Q_2 is turned off, and the desired waveform can be obtained. The driving signals are the same, whereas different output voltages appear when the zero-crossing point of i_1 varies.

Figure 2. Dead-time effect of one active bridge WPT system. (a) Dead time is inserted when $i_1 > 0$; (b) Dead time is inserted during the zero-crossing point of i_1 ; (c) Dead time is inserted when $i_1 < 0$.

Although the dead-time effect has been investigated in the grid-tied inverters, it is significantly different in the resonant systems where the frequency of the output current becomes identical to the switching frequency. In order to evaluate the voltage distortion intuitively, the product of 2γ and

the operating frequency f is defined as the voltage distortion ratio (VDR), and the maximum VDR ($VDR_{\max}$) as shown in Figure 2a can be denoted as

$$VDR_{\max} = T_d f \times 100\%. \quad (3)$$

With the increase of the operating frequency, $VDR_{\max}$ increases quickly. In [27,28], the operating frequency of the VSI ranges from 20 kHz to 200 kHz, and the dead time ranges from 0.2 μ s to 1.2 μ s. In [29], the operating frequency of the commercial evaluation design kit can be up to 300 kHz, and the required dead time should be greater than 0.45 μ s at 40 kHz. In [19], a double-side LCC WPT system operates at 95 kHz, where the adopted dead time is 0.5 μ s. Therefore, T_d is set at 0.5 μ s in this paper. The operating frequency is 305 kHz in [30] and 515 kHz in [31], whose $VDR_{\max}$ values can be 15.25% and 25.75%, respectively. If without proper configuration of the dead time, the phase errors of [30,31] can be up to 54.9° and 92.7°, respectively.

2.2. Dead-Time Effect of DAB WPT System

The active bridge analyzed in the Section 2.1 only acts as a DC/AC converter. It is a special case of phase control where the phase angle of v_1 is 90°. Actually, the dead-time effect becomes more complex when applying the phase control, especially in the DAB WPT system.

Due to the symmetry of the DAB WPT system, the analysis and elimination of the dead-time effect can be fully investigated based on one active bridge. Since secondary phase angles are independent and controllable [14], the secondary active bridge is chosen as the research object in this paper, which benefits from the experimental validation of the analysis.

With the insertion of the dead time and the usage of multiple degrees of phase control, the operating conditions of the DAB WPT system can be classified into eight regions, as shown in Figure 3. In region 1, $\beta - 90 + \theta_d < \varphi < 90 - \beta$. In region 2, $90 - \beta < \varphi < 90 - \beta + \theta_d$. In region 3, $90 - \beta + \theta_d < \varphi < 90 + \beta$. In region 4, $90 + \beta < \varphi < 90 + \beta + \theta_d$. In region 5, $90 + \beta + \theta_d < \varphi < 270 - \beta$. In region 6, $270 - \beta < \varphi < 270 - \beta + \theta_d$. In region 7, $270 - \beta + \theta_d < \varphi < 270 + \beta$. In region 8, $270 + \beta < \varphi < 270 + \beta + \theta_d$. When φ lies in the different regions, the dead-time effect varies.

Figure 3. Operating regions of DAB WPT system with dead time.

The typical dead-time effect waveforms of the DAB WPT system in eight regions are shown in Figure 4. In Figure 4a, the left part of v_2 is missing by θ_d , that is, β and φ are decreased by $0.5\theta_d$. In Figure 4b, the left part of v_2 is missing, and the fault pulses are generated. It can be regarded as that a waveform with twice amplitude and reverse phase of the missing part is added to the expected waveform. In Figure 4c, the dead time has no influence on the generation of the desired v_2 . In Figure 4d, the right part of v_2 is extended to the zero-crossing point of i_2 , which results in a greater β and a smaller φ . In Figure 4e, the right part of v_2 is extended by θ_d . β is increased by $0.5\theta_d$, whereas φ

is decreased by $0.5\theta_d$. In Figure 4f, the left part of v_2 is missing, whereas the right part of v_2 is extended by θ_d . The widths of the missing and the extending parts are different. Therefore, the error waveform consists of two periodical components. The total harmonic distortion can be calculated by using the superposition theorem twice. In Figure 4g, the left part of v_2 is missing by θ_d , and the right part of v_2 is extended by θ_d , which is equivalent to shift v_2 right by θ_d . Thus, φ is reduced by θ_d . In Figure 4h, the left part of v_2 is missing by θ_d , and a fault voltage pulse is produced as well. It is equivalent to adding two periodical error waveforms. Although the pulse widths of v_2 in the eight figures are expected to be the same, the results can vary due to the dead-time effect.

Figure 4. Dead-time effect of the DAB WPT system where the orange and yellow areas present the missing and extending parts of the voltage, respectively. (a) Region 1; (b) Region 2; (c) Region 3; (d) Region 4; (e) Region 5; (f) Region 6; (g) Region 7; (h) Region 8.

3. Dead-Time Elimination

As analyzed in the Section 2, the dead time has a great influence on the WPT systems. In this section, a novel PWM mode is presented, which is capable to remove the dead-time effect. The dead-time effect of the DAB WPT systems should be the most complex among all topologies, and their solutions can be easily applied to other resonant VSIs. Therefore, the proposed dead-time elimination method is analyzed based on the DAB WPT system.

The phase leg can be decomposed into two cells: the channel and the diode, as shown in Figure 5. i_C and i_D represent the currents flowing through the channel and the diode, respectively. i_2 can flow through the channel of S_6 or D_6 at the positive period, and through the channel of S_5 or D_5 at the

negative period. Despite the current direction, the freewheeling diode can provide a path for the current, which offers an opportunity for the dead-time elimination.

Figure 5. Decomposition of a phase leg. (a) $i_2 > 0$; (b) $i_2 < 0$.

In the conventional DAB WPT systems, there are eight operating regions as shown in Figure 3. However, without considering the dead time, the operating conditions can be simplified into four regions according to the phase angles, which are shown in Figure 6. φ ranges from 0 to 360° , and β from 0 to 90° . In region 1, $\beta - 90 < \varphi < 90 - \beta$. In region 2, $90 - \beta < \varphi < 90 + \beta$. In region 3, $90 + \beta < \varphi < 270 - \beta$. In region 4, $270 - \beta < \varphi < 270 + \beta$. When φ is greater than $270 + \beta$, it is denoted as a negative value, which belongs to region 1. During different operating regions, the system has different freewheeling paths of the resonant current. Therefore, dead-time elimination characteristic varies in four different regions.

The typical waveforms of the corresponding four regions are shown in Figure 7, where d_1 and d_2 are the lengths of the shadow areas. It is recognized that the states of the shadow areas cannot affect the generation of v_2 , where the current can freewheel through the diodes. Dead-time elimination of the DAB WPT system can be achieved by turning off the shadow area signals. Furthermore, the lengths of d_1 and d_2 can be obtained according to the following derivations.

Region 1:

φ belongs to $(\beta - 90, 90 - \beta)$, as shown in Figure 7a. Q_5 and Q_6 must be turned on after Q_6 and Q_5 are turned off respectively, providing d_1 length. However, Q_7 and Q_8 must be turned off before Q_8 and Q_7 are turned on respectively, providing d_2 length. The lengths of d_1 and d_2 are

$$d_1 = 90 - \beta + \varphi, \quad (4)$$

$$d_2 = 90 - \beta - \varphi. \quad (5)$$

Region 2:

φ belongs to $(90 - \beta, 90 + \beta)$, as shown in Figure 7b. Q_5 and Q_6 must be turned on after Q_6 and Q_5 are turned off respectively, providing d_1 length. Same operations are implemented on Q_7 and Q_8 , providing d_2 length. The lengths of d_1 and d_2 are

$$d_1 = 90 - \beta + \varphi, \quad (6)$$

$$d_2 = -90 + \beta + \varphi. \quad (7)$$

Region 3:

φ belongs to $(90 + \beta, 270 - \beta)$, as shown in Figure 7c. Q_5 and Q_6 must be turned off before Q_6 and Q_5 are turned on respectively, providing d_1 length. However, Q_7 and Q_8 must be turned on after Q_8 and Q_7 are turned off respectively, providing d_2 length. The lengths of d_1 and d_2 are

$$d_1 = 270 + \beta - \varphi, \quad (8)$$

$$d_2 = -90 + \beta + \varphi. \quad (9)$$

Region 4:

φ belongs to $(270 - \beta, 270 + \beta)$, as shown in Figure 7d. Q_5 and Q_6 must be turned off before Q_6 and Q_5 are turned on respectively, providing d_1 length. Same operations are implemented on Q_7 and Q_8 , providing d_2 length. The lengths of d_1 and d_2 are

$$d_1 = 270 + \beta - \varphi, \quad (10)$$

$$d_2 = 450 - \beta - \varphi. \quad (11)$$

The PWM mode in the proposed method provides an available time for current freewheeling without affecting neither β nor φ . However, as in the borders mentioned above, two special cases should be noticed. One is the border between region 1 and region 2 where d_2 becomes 0, as can be indicated by (5). The other is the border between region 1 and region 4 where d_1 becomes 0, as can be indicated by (4). Therefore, it is recommended not to operate near these two borders. If necessary, dead time should be added between the complementary driving signals.

Figure 6. Operating regions of the DAB WPT system without dead time.

Figure 7. Dead-time elimination regions in the DAB WPT system where the driving signal in the shadow areas can be turned off. (a) Region 1; (b) Region 2; (c) Region 3; (d) Region 4.

The flowchart of the calculation of d_1 and d_2 is shown in Figure 8. First, configure the value of β and φ . Then, discriminate the corresponding phase region. Afterwards, calculate the values of d_1 and d_2 according to (4)–(11). Finally, the corresponding compared values of the reserved registers of the controller are reconfigured based on the region, β , φ , d_1 , and d_2 , which generates the desired driving signals. Since the proposed modulation varies with four regions as analyzed in Figure 7, four compared value calculation functions are provided in the program. If the system needs to transit from one region to another, recalculate the compared values according to the corresponding function and reload them into the reserved registers.

Figure 8. Calculation of d_1 and d_2 .

4. Simulations and Experiments

To verify the feasibility and effectiveness of the proposed method, a simulation model in MATLAB/Simulink (R2017a, MathWorks, Natick, MA, USA) and a prototype system have been built. The prototype photograph of the system is shown in Figure 9, whose parameters are listed in Table 1. According to SAE J2954 [32], the operating frequency must remain in the range of 81.38 kHz to 90 kHz. In this paper, the operating frequency is set at 90 kHz, where the dead-time effect is more obvious. The primary and secondary active bridges consist of four half bridges where eight C2M0080120D MOSFETs and eight C4D20120D diodes are used. The primary and secondary DC voltages are connected, and the voltage source only needs to supply the power losses of the system, which is widely adopted in the test of the DAB systems. Both the primary and secondary compensation capacitors are made up of two 0.1 μF AC capacitors in series. The inner and outer radii of the coils are 16 cm and 19 cm, respectively. Two magnetic core layers are utilized to shield the magnetic field and increase the mutual inductance. The air gap (d) between the transmitting and receiving coils is 10 cm with a mutual inductance of 14 μH measured by LCR meter TH2830. The waveforms are observed and recorded by Tektronix TPS2024B (Tektronix, Beaverton, OR, USA).

Table 1. Key parameters of the proposed system.

Symbol	Parameter	Value
$V_{1,\text{dc}}$	primary DC voltage	100 V
$V_{2,\text{dc}}$	secondary DC voltage	100 V
L_1	transmitter coil inductance	61 μH
C_1	transmitter compensation capacitance	0.05 μF
L_2	receiver coil inductance	61 μH
C_2	receiver compensation capacitance	0.05 μF
f	inverter frequency	90 kHz
d	the air gap between the coils	10 cm
M	mutual inductance	14 μH

Figure 9. Prototype photograph of the DAB WPT system.

4.1. Dead-Time Effect

Figures 10 and 11 show the simulated and experimental results of the eight kinds of dead-time effect in the DAB WPT system, where the dead time is set at $0.5 \mu\text{s}$. The given β is 45° . According to Equation (3), the value of VDR_{max} of this system is 4.5%, corresponding to 16.2° phase error. Due to limited channels of the oscilloscope, different experimental driving signals are selected to display for better judgement of the region. In Figures 10a and 11a, the given φ is 335° , and the zero-crossing point of i_2 falls into region 1. The left part of v_2 is missing by 16.2° , that is, the actual φ and β become 326.9° and 36.9° , respectively. In Figures 10b and 11b, φ is 47° , and the zero-crossing point of i_2 falls into region 2 (within the dead time). The left part of v_2 is missing, which results in the appearance of the error pulse voltage. Since the pulse width is small and the voltage changes slowly during the zero-crossing point of i_2 , the experimental v_2 decreases before reaching the peak. φ and β become 38.9° and 36.9° , respectively. In Figures 10c and 11c, φ is 120° , and the zero-crossing point of i_2 falls into region 3. The dead time does not affect the generation of v_2 . In Figures 10d and 11d, the given φ is 140° , and the zero-crossing point of i_2 falls into region 4 (within the dead time). The right part of v_2 is extended to the zero-crossing point of i_2 , where v_2 changes its state slowly in the experiment. φ and β become 137.5° and 47.5° , respectively. In Figures 10e and 11e, the given φ is 210° , and the zero-crossing point of i_2 falls into region 5. The right part of v_2 is extended by 16.2° , i.e., φ and β become 201.9° and 53.1° , respectively. In Figures 10f and 11f, the given φ is 228° , and the zero-crossing point of i_2 falls into region 6 (within the dead time). The left part of v_2 is missing until the zero-crossing point of i_2 , whereas the right part of v_2 is extended by 16.2° . φ and β become 218.4° and 51.6° , respectively. In Figures 10g and 11g, the given φ is 238° , and the zero-crossing point of i_2 falls into region 7. The left part of v_2 is missing by 16.2° , whereas the right part is extended by 16.2° . Therefore, φ becomes 221.8° , and β remains unchanged. It is equivalent to shift v_2 right by 16.2° . In Figures 10h and 11h, the given φ is 319° , and the zero-crossing point of i_2 falls into region 8 (within the dead time). The left part of v_2 is missing by 16.2° , along with a fault pulse voltage. φ and β become 310.9° and 36.9° , respectively. The simulated and experimental results agree well with the analysis in Section 2.

As evident from the simulated and experimental illustrations, the system can operate as desired only in the region 3, in comparison with the eight operating regions, when inserting the dead time. Moreover, the voltage reverses thrice within a short time during the region 2 and the region 8, which can damage the semiconductors. Therefore, the dead-time effect in the DAB WPT system becomes problematic, and it should be addressed well in the practical applications.

Figure 10. Simulated results of the eight kinds of dead-time effect in the DAB WPT system. (a) Region 1; (b) Region 2; (c) Region 3; (d) Region 4; (e) Region 5; (f) Region 6; (g) Region 7; (h) Region 8. i_2 : 5 A/div; v_2 : 50 V/div.

Figure 11. Experimental results of the eight kinds of dead-time effect in the DAB WPT system. (a) Region 1; (b) Region 2; (c) Region 3; (d) Region 4; (e) Region 5; (f) Region 6; (g) Region 7; (h) Region 8. Q_5 – Q_8 : 5 V/div; i_2 : 5 A/div; v_2 : 50 V/div.

4.2. Dead-Time Elimination

Figures 12 and 13 show the simulated and experimental results of the dead-time elimination in the reclassified four regions. To avoid the incorrect operation, 5° phase redundancy is adopted, i.e., the actual d_1 and d_2 are 5° smaller than the calculated values. In Figures 12a and 13a, φ is 0° , and the zero-crossing point of i_2 falls into region 1. Both d_1 and d_2 are 40° . In Figures 12b and 13b, φ is 120° , and the zero-crossing point of i_2 falls into region 2. d_1 and d_2 are 160° and 70° , respectively. Thus, the lengths of the valid voltages of Q_5 and Q_6 are only 20° . In Figures 12c and 13c, φ is 180° , and the zero-crossing point of i_2 falls into region 3. Both d_1 and d_2 are 130° . In Figures 12d and 13d, φ is 245° , and the zero-crossing point of i_2 falls into

region 4. d_1 and d_2 are 65° and 155° , respectively. The actual β and φ are equal to the given values in the four regions. The transmitting DC power of the simulations reaches 541 W with 92.1% DC–DC efficiency, as shown in Figure 12c. The transmitting DC power of the experiments reaches 645 W with 88.7% DC–DC efficiency, as shown in Figure 13c.

In the proposed PWM mode, the driving signals of the same phase leg are no longer complementary to each other, and consequently, the dead time is not necessary. The desired output voltage can be generated in all the regions. The simulated and experimental results validate the feasibility and effectiveness of the proposed dead-time elimination method.

In order to demonstrate the validity of the analysis, d_1 and d_2 are designed as large as possible in this paper. In practice, d_1 and d_2 can be adjusted based on the specific operating conditions, and ensure the current flowing through the channel as long as possible, which can reduce the conduction losses.

Figure 12. Simulated results of proposed dead-time elimination method. (a) Region 1; (b) Region 2; (c) Region 3; (d) Region 4. i_2 : 5 A/div; v_2 : 50 V/div.

Figure 13. Experimental results of proposed dead-time elimination method. (a) Region 1; (b) Region 2; (c) Region 3; (d) Region 4. Q_5 – Q_8 : 5 V/div; i_2 : 5 A/div; v_2 : 50 V/div.

4.3. Comparisons and Discussions

The differences between the expected and the actual phase angles ($\Delta\beta$ and $\Delta\varphi$) of conventional PWM mode and proposed PWM mode are shown in Table 2. In the conventional PWM mode, the dead time is inserted. $\Delta\beta$ can increase or decrease in the different regions, whereas $\Delta\varphi$ can only decrease. The maximum positive $\Delta\beta$ is 8.1° appearing in region 5, whereas the maximum negative $\Delta\beta$ is -8.1° appearing in region 1, region 2, and region 8. The maximum negative $\Delta\varphi$ can be up to -16.2° , appearing in region 7. $\Delta\beta$ and $\Delta\varphi$ are 0° only in region 3. In the proposed PWM mode, dead-time elimination is achieved, and the phase errors are 0° in all the regions. In [11–14], β and φ are used to realize the impedance matching for maximum efficiency point tracking. The phase errors between the given and the actual values can result in control performance deterioration. Furthermore, it can affect the transferred power and generate undesired harmonics.

Table 2. Comparisons between conventional and proposed PWM modes.

PWM Modes	Regions	$\Delta\beta$	$\Delta\varphi$
Conventional PWM mode	Region 1	-8.1°	-8.1°
	Region 2	-8.1°	-8.1°
	Region 3	0°	0°
	Region 4	2.5°	-2.5°
	Region 5	8.1°	-8.1°
	Region 6	6.6°	-9.6°
	Region 7	0°	-16.2°
	Region 8	-8.1°	-8.1°
Proposed PWM mode	Region 1	0°	0°
	Region 2	0°	0°
	Region 3	0°	0°
	Region 4	0°	0°

Although solutions of dead-time effect have been investigated in the low output current frequency applications [18,20–26], they cannot be applied to the WPT systems where the output current frequency is identical to the switching frequency. The researchers in [19] realize the significant influence of the dead time on the WPT systems, and derive the optimal dead time based on one condition. Although the dead time is a common issue of VSIs, a very few literature studies comprehensively discuss its effects in the WPT systems and explore the elimination methods. As evident from the simulated and experimental results, the proposed technique can effectively control the dead-time effect of the WPT systems up to a certain extent, which contributes to the realization of flexible power conversion. In addition, the proposed method is not influenced by the system parameters. Generally, only high performance and expensive semiconductor devices with short rise and fall times can operate at a high frequency. However, by employing the proposed dead-time elimination method, the freewheeling period can be fully utilized as shown in Figures 12 and 13, and common semiconductor devices can work at a higher frequency in the resonant systems, which can reduce the cost.

5. Conclusions

This paper investigates the possible dead-time effect of the WPT systems and presents a novel dead-time elimination method based on the SS DAB topology. Considering the dead time, the operating conditions of the DAB WPT system can be divided into eight regions. However, the system can operate properly only in one region, and different voltage distortions appear in the other seven regions. Maximum phase error can be up to 16.2° at 90 kHz with $0.5\ \mu\text{s}$ dead time. By utilizing the freewheeling diode, some states of the driving signals cannot affect the resonant voltages, and they can be turned off for dead-time elimination. Without considering the dead time, the DAB WPT system can be reclassified into four operating regions, and the expressions of the lengths of the inessential driving signals are

derived. Through the proposed PWM mode, the desired waveform can be generated correctly in all four regions. A simulation and a prototype with over 500 W transmitting power are established, and the results validate the efficacy of the proposed analysis.

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