Dead-time Compensation Method for Dual Active Bridge Converter with Three-level Operation

Jun-ichi Itoh , Kengo Kawauchi , Hayato Higa
Nagaoka University of Technology

This paper proposes a compensation method of a transferred power error for a dual active bridge (DAB) converter. At light load, the error of the transferred power occurs due to dead time, which is conventionally compensated by using feedforward control. However, the dead-time error due to neutral point clamping cannot be compensated by the conventional method because the error is varied depending on the width of the neutral point clamping. In the proposed method, the neutral point clamping can be avoided by using three-level operation. Thus, the feedforward control compensation can still be applied to correct the transferred power error. The validity of the proposed method is confirmed by a 2.5 kW prototype. As experimental results, the error of the transferred power is reduced from 101% to 2.84%.

Keywords Dual active bridge converter, Dead-time compensation, Three-level operation

1. Introduction

In recent years, energy storage systems for electric vehicles and smart grid system have been actively researched [1]. In the energy storage system, a bidirectional operation and a galvanic isolation are required. In order to satisfy these requirements, a bi-directional isolated DC-DC converter is necessary in the energy storage system. In general, dual active bridge (DAB) converters are generally employed. The DAB converters can achieve zero voltage switching (ZVS) without any additional component. However, at light load, the error of the transferred power occurs due to neutral point clamping which is caused by dead time [2].

In order to reduce the error of the transferred power, the dead-time compensation has been proposed by using a feedforward control [3]. However, the dead-time error due to the neutral point clamping cannot be compensated by the conventional method because the transferred power error is varied depending on the width of the neutral point clamping.

This paper proposes a transferred-power error-compensation method at light load for the DAB converter by applying the three-level voltage including a zero-voltage period, i.e. three-level operation. By applying the three-level operation, the neutral point clamping is avoided because the zero-voltage period and phase-shift angle can be controlled. In order to confirm the validity of the proposed method, experiments with a 2.5-kW prototype are conducted.

2. Circuit structure and operation principle

Fig. 1 shows circuit configuration of the DAB converter. The primary and secondary inverters output the square-wave voltage or the three-level voltage including the zero-voltage period, which is categorized as two-level operation and three-level operation. Note that the three-level operation is then divided into two sub operation mode.

Fig. 2 shows the operation waveform of the two-level operation with/without the dead time. In Fig. 2(a) the transferred power is controlled by the phase-shift angle δ between the output voltages of two inverters [3]. When the dead time is introduced, the transferred power error occurs because the neutral point is clamped due to the dead time.

Fig. 3 shows the operation waveform of two modes of three-level operation with/without the dead time. Fig. 3 (a) and (b) show two modes of the three-level operation without the dead time. In particular, both operation modes of the three-level operation equalize the length of both inverters output zero voltage period ε and γ. By using two modes of three-level operation, the transferred

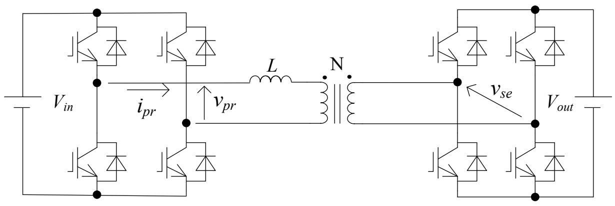


Fig. 1. Dual active bridge converter.

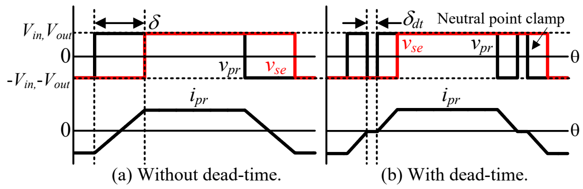


Fig. 2. Operation waveform with 2-level operation.

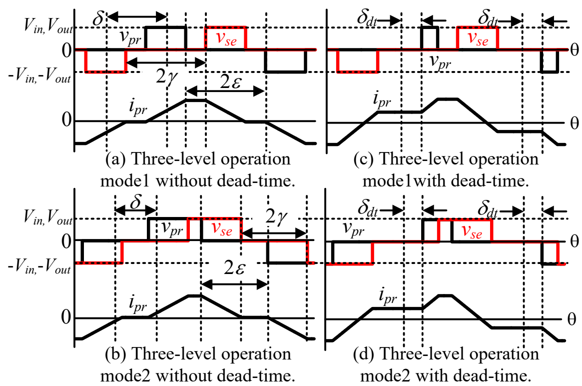


Fig. 3. Operation waveform with 3-level operation.

power error compensation can be applied over wide load range. The neutral point clamp can be avoided because the three-level operation can adjust the zero voltage period and the phase-shift. Fig.3 (c) and (d) show two modes of the three-level operation with the dead time. The transferred power error of the two-level operation is caused by the neutral point clamping. In contrast, the transferred power error of the three-level operation is not caused the neutral point clamping, but simply by the dead time voltage error. Hence, the transferred power error of three-level operation can be compensated by the conventional dead-time compensation.

Fig. 4 shows a flowchart to determine operation modes. It should be noted that the flowchart is based on the condition of V_{in}=V_{out}. Firstly, the phase-shift angle δ is calculated by the relationship between the phase-shift angle δ and the transferred power P_{ref} [1]. The operation mode is decided by the phase-shift angle δ and the dead time δ_{dt}. Under the condition of $\delta_{ref}>2\delta_{dt}$, the

Correspondence to: Jun-ichi Itoh. E-mail: itoh@vos.nagaokaut.ac.jp,
Nagaoka University of Technology
1603-1, Kamitomioka-machi, Nagaoka, Niigata, Japan, 940-2188

two-level operation is applied. In contrast, the three-level operation is used in the condition of $\delta_{ref} \leq 2\delta_{dt}$. The three-level operation with mode 1 is applied when the zero-voltage period ε satisfies (1).

$$\varepsilon > \pi/4 + 1/2\delta_{dt} \tag{1}$$

Then, the zero-voltage period ε is given by (2) in order to output the reference transferred power P_{ref}.

$$\varepsilon = \frac{1}{2}\left(\pi - \sqrt{2\pi\omega L P_{ref} / V_{in}^{2}}\right) \tag{2}$$

The transferred power P_{ref} is determined only by the zero-voltage period ε because the phase-shift δ does not affect the transferred power P.

At the condition that (1) is not established, the DAB is operated by the three-level operation with mode 2. In this mode, the zero voltage period ε is calculated by (3) in order to the output reference transferred power P_{ref}.

$$\varepsilon = \frac{1}{4}\left(2\pi - \delta - 2\pi\omega L P_{ref} / \delta V_{in}^{2}\right) \tag{3}$$

Note that the phase-shift δ in (3) is defined as a constant in order to reduce a degree of freedom. By using two types of the three-level modes, the transferred power error still occurs but it is caused by only the dead time voltage error. Equations in (4) indicate the reference values considering the dead-time voltage error compensation.

$$\delta_{ref} = \delta_{const} + \delta_{dt}/2$$
$$\varepsilon_{ref} = \varepsilon - \delta_{dt}/2 \tag{4}$$
$$\gamma_{ref} = \varepsilon$$

Note that when mode 1 is applied, δ_{const} is $\pi/2$ rad. Otherwise, when the mode 2 is applied, δ_{const} is $\pi/4$ rad.

3. Experimental results

Table 1 shows the experimental parameters. A 2.5 kW prototype of the DAB converter is tested in order to confirm validity of the transferred power compensation using the three-level operation.

Fig. 5 shows the operation waveforms with the two-level operation and the three-level operation. By applying the three-level operation, the neutral point clamping is avoided. In Fig. 5(a) and (b), the error of the transferred power is reduced from 58.2% to 6.18%.

Fig. 6 shows the characteristics of the transferred power against the reference transferred power. When using only two-level operation, the transferred power at light load becomes 0 W because the phase reference δ is smaller than the dead time δ_{dt}. By applying the three-level operation, the transferred power error at light load is reduced compared with that of two-level operation. However, the maximum error of 11.3% of the three-level operation in the boundary between the two-level operation and the three-level operation because the period of the dead time is long for mode 2. The operation mode at the changing point of two modes is derived in future work.

4. Conclusion and future work

This paper proposed the transferred power error compensation method for the DAB converter with three-level operation. In the proposed method, the error of the transferred power is reduced from 101% to 2.84%.

In future work, the operation mode at the changing point between the two-level and the three-level operation will be considered.

References

[1] F. Krismer, IEEE Trans. PELS., Vol. 27, No.1, (2012)
[2] B. Zhao, et al: IEEE Trans. PELS, Vol.29, No.4, (2014)
[3] D. Segaran, et al: IEEE Trans. PELS, Vol.28, No.1, (2012)

Table 1. Experimental parameters.

Input voltage	100 V	Leakage inductance	24 μH
Output voltage	100 V	Transformer turn ratio	1
Rated power	2.3 kW	Dead time	3.2 μs
Switching frequency		20 kHz	

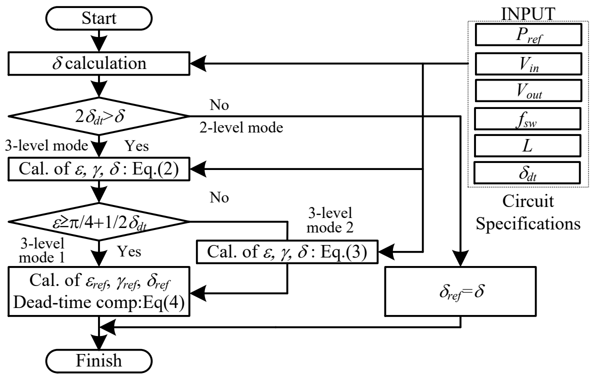
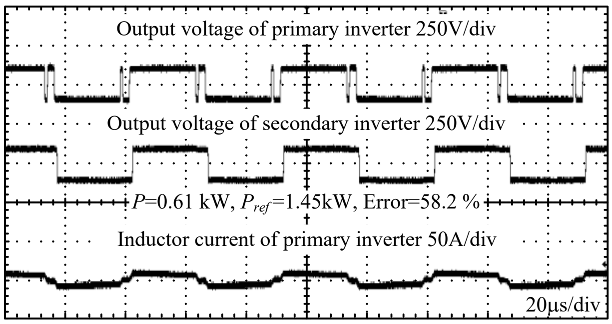
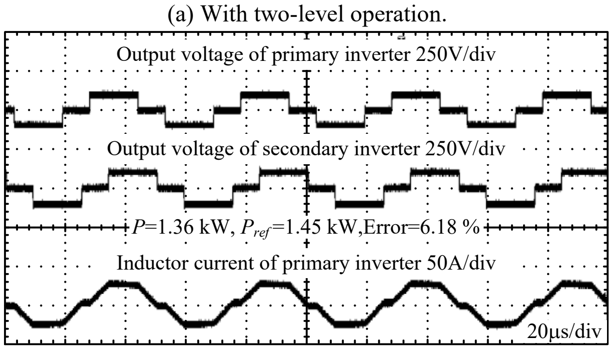


Fig. 4. Flowchart of determination of operation mode.



(a) With two-level operation.



(b) With three-level operation.

Fig. 5. Experimental waveform of two-level operation and three-level operation.

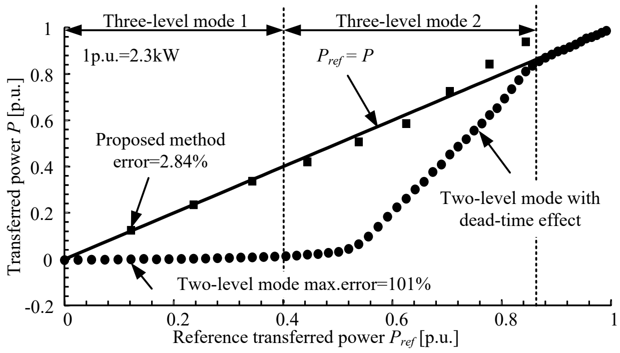


Fig. 6. Characteristics of transferred power.