Voltage Balancing Control of Bidirectional Input-Series Output-Series (ISOS) Dual Active Bridge DC/DC Converters without Auxiliary Circuits

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Abstract

A Dual Active Bridge (DAB) converter[1] is compact and capable of DC power isolation and power flow control. Until now, studies have been conducted to connect DAB converters in an Input-Series Output-Series (ISOS) to support higher voltage DC. In this configuration, it is necessary to equally balance the voltages applied to each DAB converter. Power cannot, however, be transferred between upper and lower DAB converters. For this reason, once balance is lost, it is impossible to restore the balance, making it extremely difficult to realize ISOS connection of the DABs.

The recently devised balance control method takes advantage of the fact that the output side of power is stable, and controls only the input side. Under conditions where the power flow is reduced and stability is degraded, the excess voltage is discharged by utilizing the loss. Unlike previous research, we verified through mini-model experiments that voltage balance could be maintained without using any auxiliary circuits in the configuration with more than two units.

1 Preface

A Dual Active Bridge (DAB) converter[1] is a power converter that consists of two inverters and a small high-frequency transformer. An inverter on one side converts DC power into high-frequency AC power and inputs it to the transformer. The electrical current flows through the transformer and isolated. The power is returned to DC power using the inverter on the other side. This allows DC power to be isolated. A feature of a DAB converter is that it uses a high frequency, so a small transformer can be used. Furthermore, the amount of power exchanged is adjusted by the phase difference between the AC output voltages of the two inverters. This also allows for power interchange from the low voltage side to the high voltage side. A DAB converter has a configuration suitable for DC isolation and power flow control.

Fig. 1 shows the Input-Series Output-Series (ISOS) connection configuration of *m* numbers of DAB converters. DAB converters can handle higher voltage DC power by connecting multiple units in series on both the primary and secondary sides. In this configuration, it is important to maintain the DC

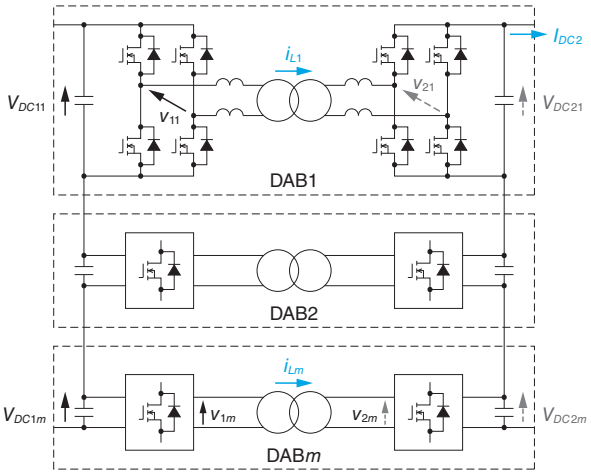


Fig. 1 DAB Converters Connected in ISOS

Since the primary and secondary circuits are isolated by a transformer, it is possible to establish a system configuration for a combination of multiple DAB converters. By connecting the input and output circuits in a series, it is possible to handle higher voltages. Consequently, there appears to be a challenge to maintain the DC voltages uniformly for the respective DABs.

voltage applied to each converter equally. If either the primary or secondary DC voltage becomes unbalanced, abnormal voltage may be applied to a particular DAB converter, potentially damaging it. Power interchange, however, is limited to the primary and secondary parts of the same DAB converter. In other words, power cannot be transferred from a DAB converter with excessive DC voltage to another DAB converter with insufficient DC voltage. It is, therefore, difficult to maintain voltage balance.

In document (2), a small-capacity auxiliary circuit is added to maintain voltage balance, and it is possible to connect two different DAB converters. A method has been proposed that allows power to be transferred among the DABs, as is also a smaller capacity auxiliary circuit being considered. However, an insulation design that increases its volume. In so doing, the number of parts may also increase. To achieve miniaturization and lower failure rates, it is preferable not to have auxiliary circuits.

Document (3) successfully eliminates any auxiliary circuits by controlling only the voltage balance on the input side using two series-connected DAB converters. However, neither series of configuration of three or more DABs, nor conditions when the amount of power interchange is extremely small, are mentioned. In addition, this investigation is limited to simulation only.

This paper introduces a voltage balance control method for series-connected DAB converters that do not require any auxiliary circuits. It can support three or more DABs and can also handle conditions with small interchangeable power. In **Section 2.1**, we will clarify that the balance on the output side is stable when the amount of power exchange is large by looking at the behavior of the circuit. A control method for the input side will be also explained. In **Section 2.2**, an additional control method when the interchangeable power is small will be introduced. In **Section 3**, the effectiveness of the proposed balance control method is confirmed by a mini-model experiment using three DABs. The conclusion of this paper is given in **Section 4**.

2 Balance Control Method

2.1 In Case that Interchangeable Power is Available

Fig. 2 shows the effect of voltage disturbance on two DAB converters with an ISOS connection. This assumes that while both the upper and lower DABs are at a transferring constant and equal power from the primary side to the secondary side, the DC voltage of the upper DAB increases due to some disturbance.

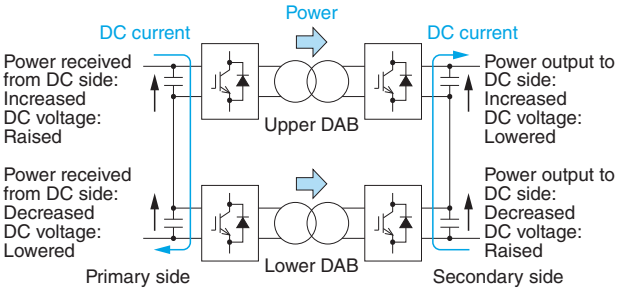


Fig. 2 **Effect of Voltage Disturbance on Two DAB Converters with ISOS Connection**

On the primary side where power is received, operation becomes unstable because of expanded deviation of DC voltage due to external turbulence. It is, therefore, necessary to control the interchanged power in response to the DC voltage. On the secondary side where power is sent out, operation is stable and the DC voltage tends to be uniform without any control.

First, considering how the DC voltage on the primary side will initially change, the DC current flowing from the left DC system to the primary side of the upper and lower DABs is common. The power received from the DC System to the upper DAB, which has a higher voltage, increases. The DABs' interchange power is constant. In the upper DAB, excess power is charged into a capacitor, and the DC voltage increases. As a result, the power received by the upper DAB further increases. The lower DAB receives less power from the grid because the DC voltage is lower. The insufficient power discharges the capacitor, causing the DC voltage to decrease further. From the above, the voltage balance on the primary side is unstable, and once it begins to become unbalanced, the voltage difference continues to increase. The difference in DC voltage on the primary side should, therefore, be detected and the interchange power of each DAB should be adjusted accordingly. This keeps the voltage balance on the primary side constant. In this example, the DC voltage can be maintained evenly by temporarily increasing the power interchange of the upper DAB and decreasing the accommodating power of the lower DAB.

Next, changes in the DC voltage on the secondary side is considered. The DC current that flows from the secondary side of the upper and lower DABs to the right DC system is common. The

power output to the grid by the upper DAB, which has a higher voltage, increases. DAB's interchange power is assumed to be constant as before. In the upper DAB, the power is insufficient, the capacitor is discharged, and the excess DC voltage is reduced. As a result, the power sent out by the upper DAB is reduced. The discharge speed of the DC voltage becomes slower. The lower DAB with a smaller voltage, however, reduces the amount of power sent to the grid. The capacitor is charged by the excess power, and the DC voltage increases. These changes in both DABs' DC voltages reach an equilibrium when the interchange power and the power sent to the right DC system become equal. The secondary DC voltage is balanced. A spontaneous voltage balancing effect then works on the secondary side making it is stable. There is, therefore, no need to detect DC voltage or adjust the interchangeable power. By performing balance control only on the primary side, the secondary side is also balanced. It enables stable operation of the DABs connected in the ISOS.

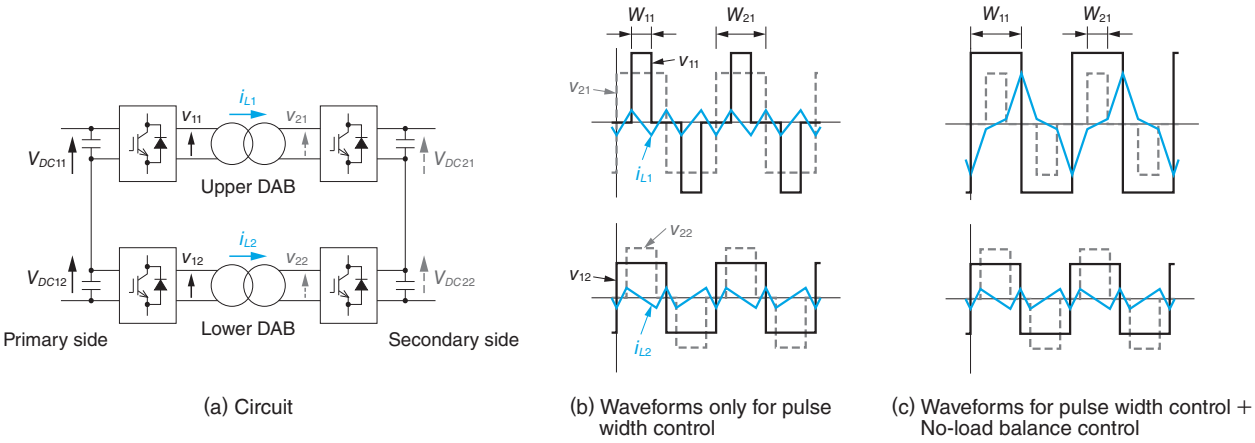
If the direction of power interchange is reversed, unlike the previous case, the voltage balance on the secondary side will become unstable and control will be required. Since the spontaneous balancing action acts on the primary side, however, no control is required. The control target, therefore, should be switched depending on the direction of power interchange. This enables balance control that accommodates power interchange in both directions.

2.2 In Case There is No Accommodating Power

The spontaneous balancing effect explained in the previous section becomes stronger as the accommodating power increases. The effectiveness decreases as the interchangeable power also decreases. This is particularly ineffective in no-load situations where the interchangeable power is 0, so an additional countermeasure is required.

Fig. 3 shows the AC side waveform of two DAB converters connected in ISOS under no load; (a) shows a case where two DABs are connected in ISOS and an imbalance occurs in the DC voltage on the primary side. In this paper, pulse width control is applied to the DAB converters for not only deceasing loss, but also for balance control in the no-load. First, this control adjusts the pulse width of the AC output voltage. This reduces the AC current and suppresses conduction loss and copper loss. To reduce the AC current, it is sufficient to equalize the inverter output voltages on the primary and secondary sides. If there is a difference between the DC voltages on the primary and secondary sides, the pulse width of one side should be adjusted so that the fundamental wave components of the inverter output voltage are equal. The DC voltage of the upper DAB is V_{DC11}. The AC voltage v_{11} becomes a rectangular wave with an amplitude V_{DC11}. When the pulse width is set to W_{11} , the amplitude V_{11} of the fundamental wave component of v_{11} is expressed by the following expression.

$$V_{11} = \frac{4V_{DC11}}{\pi} \sin\frac{\pi W_{11}}{2} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$



(a) Circuit

(b) Waveforms only for pulse width control

(c) Waveforms for pulse width control + No-load balance control

Fig. 3 AC Side Waveforms of Two DAB Converters Connected in ISOS under No Load

The pulse widths of AC voltage are regulated to reduce the AC current so that loss generation is reduced. In the case of the upper DAB where the voltage is excessive, the pulse width on high-voltage side is expanded to narrow the pulse width on low-voltage side to discharge by increasing the losses.

For the secondary side, amplitude V_{21} of the basic wave component can be similarly expressed with the use of DC voltage V_{DC21} and pulse width W_{21}.

$$V_{21} = \frac{4V_{DC21}}{\pi} \sin\frac{\pi W_{21}}{2} \quad \cdots\cdots (2)$$

When in a no-load condition, to reduce the basic wave component to zero for the current flowing in the high-frequency transformer, $V_{11} = V_{21}$ must hold. When W_{21} is given under the condition of $V_{DC11} > V_{DC21}$, the wanted W_{11} can be obtained from the expression below.

$$W_{11} = \frac{2}{\pi} \sin^{-1}\frac{V_{DC21}\sin(\pi W_{21}/2)}{V_{DC11}} \quad \cdots\cdots (3)$$

Example (b) shows the waveforms of the AC voltage and current when this pulse width determination way is applied. The AC current is reduced by narrowing the pulse width on the high side of the DC voltage. This makes it possible to suppress conduction loss and copper loss.

Example (c) shows the waveform when the balance control is enabled. In the upper DAB where the primary side's DC voltage is excessive, the pulse width W_{11} calculated using expression (3) is increased further, and the pulse width W_{21} of the lower DC voltage is decreased. This increases the current flowing through the high frequency transformer. Additionally, excessive DC voltage can be discharged by intentionally increasing conduction loss and copper loss. In the lower DAB converter, whose DC voltage is insufficient, discharge is suppressed by maintaining the minimum conduction loss and copper loss without changing the pulse width. As a result of the above, voltage balance can be maintained using loss, even in the no-load.

3 Experimental Results

To confirm the effectiveness of the balance control described above, an experiment is conducted with a mini model equipment. Fig. 4 shows the circuit for the examination of the proposed balance control. The three DAB converters are connected to both inputs and outputs in a series. The switching frequency is set to 10 kHz, the primary side DC voltage is set to 240 V per unit, and the secondary sides were set to 90 V. Since the turns ratio of the high-frequency transformers are 4:3, the voltage differences between the primary and secondary are equivalently doubled. The rated power for interchange of the whole mini model is 16.9 kW. As a disturbance to the voltage balance, a 333 Ω discharge resistor with a switch was connected to the primary side of the DAB3 at the bottom. The loss due to this discharge resistance was 3%. The transient response of the DC voltage is confirmed when the resistor is turned on with the switch.

Fig. 5 shows the DC voltage waveform during the rated power interchange. Ripples of 20 kHz or higher, which theoretically occur, are removed from the waveform. Although the discharge resistor was turned on at time 0 s, there was no difference in the waveform depending on whether control was applied or not. This causes the balancing effect due to the switching loss. As the DC voltage increases,

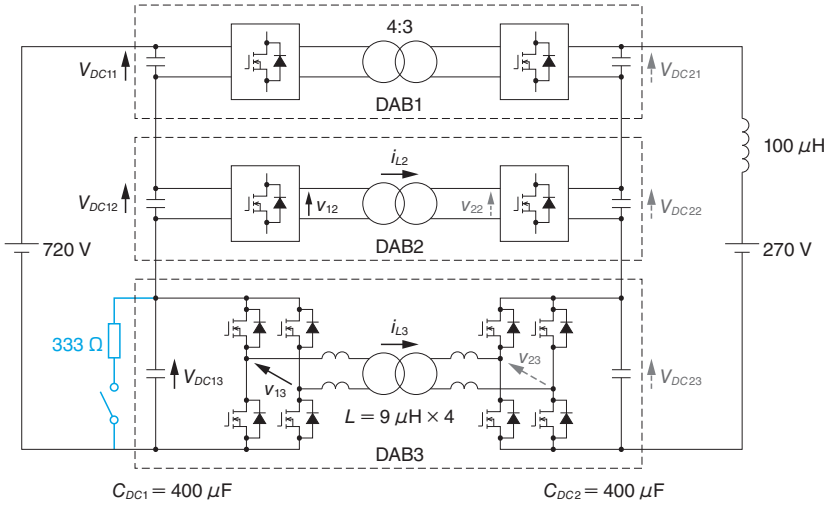
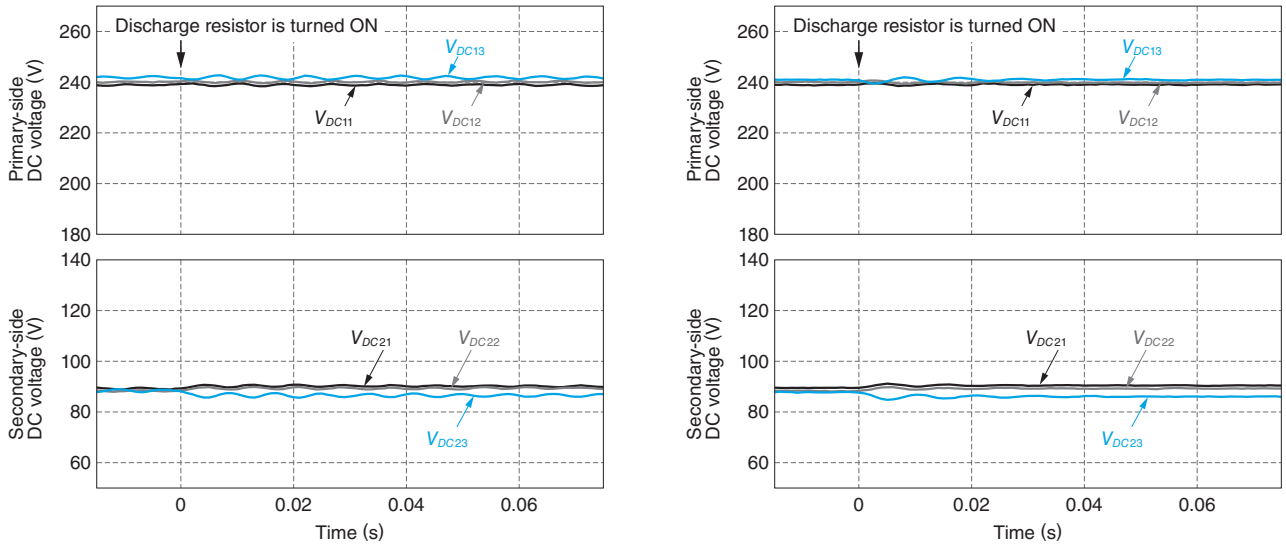


Fig. 4 Circuit for Examination of Proposed Balance Control

A circuit configuration is shown for the three DAB converters in an ISOS connection. The voltage of the primary side is set to twice the secondary side and the discharge resistor is assumed to be an external turbulence for DAB3. In this state, changes in the DC voltages are observed for the respective DABs.

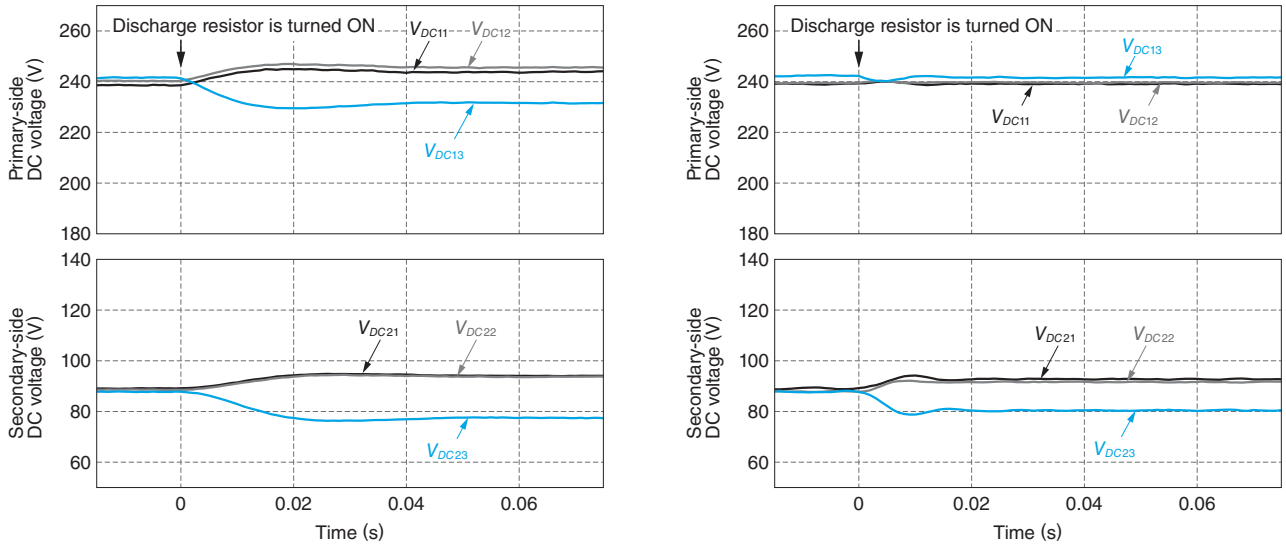


(a) Without balance control

(b) With balance control

Fig. 5 DC Voltage Waveform during Rated Power Interchange

If the interchanged power is sufficiently large, the system operation is stable even without any balance control because of the spontaneous balancing effect by the switching losses.



(a) Without balance control

(b) With balance control

Fig. 6 DC Voltage Waveform at 24% Power Interchange

When the interchanged power is decreased, the stability is reduced without any control. When balance control is conducted, deviation keeps small on the primary side that is the object of control. Even on the secondary side which is not the object of control, deviation can be made smaller compared with the case of no control.

switching loss also increases, promoting discharge. As the DC voltage decreases, switching loss also decreases and discharge is suppressed. When the interchangeable power is large enough, the voltage balance is highly stable without any control.

Fig. 6 shows the DC voltage waveform at 24% power interchange. As the load decreases, the balance effect due to switching loss weakens, so there are clear differences in waveforms depending on whether balance control is used or not. If the balance control is disabled, the deviations on both sides increase after the discharge resistor is turned on. If the control is effective, the deviation on the primary side, which is the target of control, will keep small before and after turning on the discharge resistor. Although the deviation increases on the

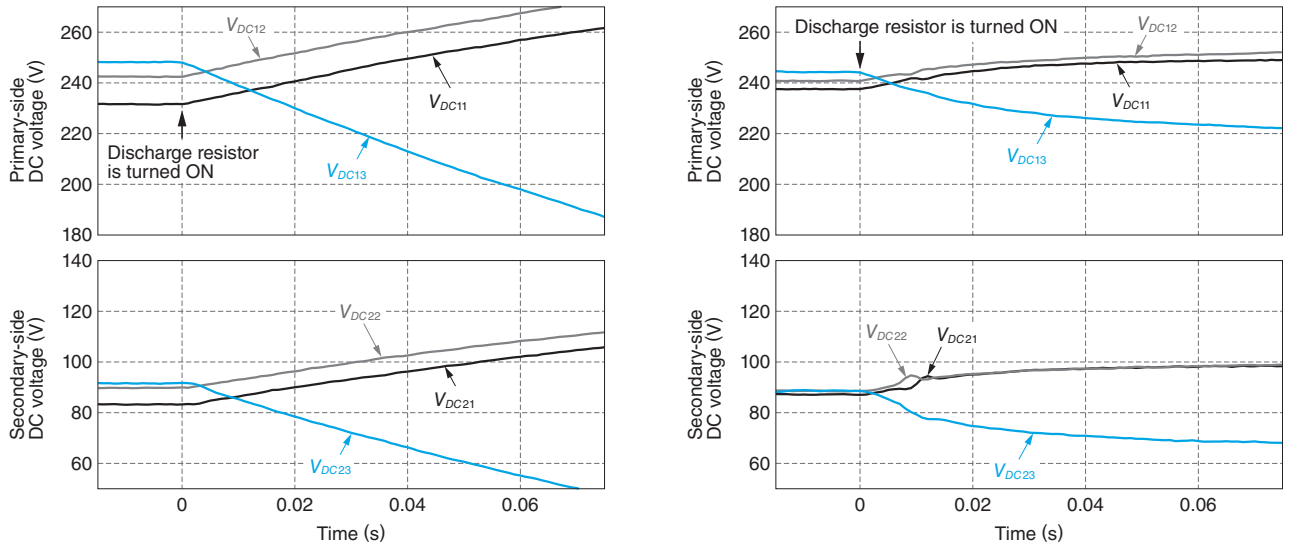


Fig. 7 **DC Voltage Waveforms at 0% Power Interchange (No Load)**

When no balance control is implemented, deviations continue to increase and the mini-model stops its operation. When balance control is implemented, deviations stop increasing and the mini-model can continue operation.

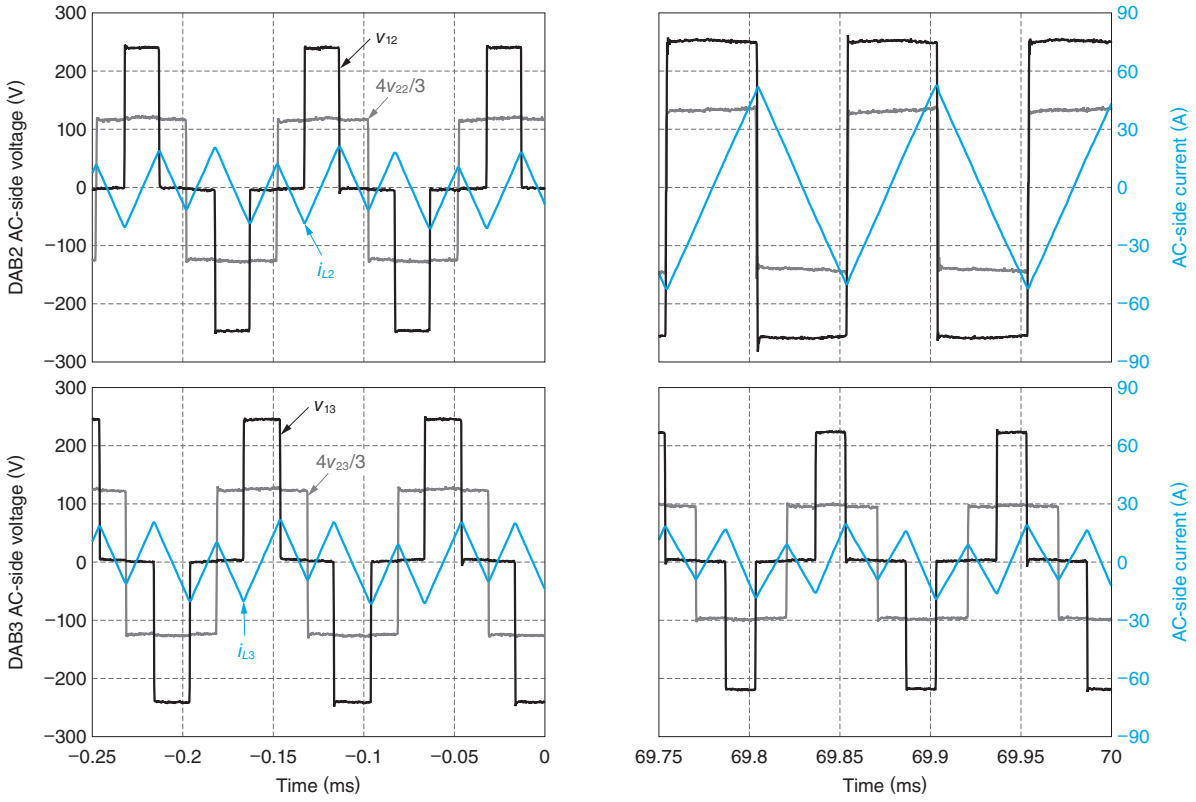
secondary side, which is not subject to control, the deviation is smaller than that without balance control.

Fig. 7 shows the DC voltage waveform at 0% power interchange (no load). Balance control using loss is performed only under these conditions. The difference in waveforms with and without balance control became even more remarkable. Without control, the deviation would continue to increase, and the mini model equipment would detect overvoltage and stop, making it impossible to continue operation. By enabling the control, although the deviation increases, it is confirmed that the increase stops and operation can continue.

Fig. 8 shows the AC side waveforms at 0% power interchange (no load); (a) is the AC side waveforms of DAB2 and DAB3 before turning on the discharge resistor with no load and (b) is after turning on the resistor. The discharge resistor was turned on at time 0 s. The pulse width of AC voltages v_{12} and v_{13} on the primary side, which is the high voltage side, of both DAB2 and DAB3 has become narrower, and the fundamental wave components of AC currents i_{L2} and i_{L3} can be suppressed to almost 0. In the waveform (b), the waveform of DAB3, which has a discharge resistance, does not change. As a result, the fundamental wave of the AC current i_{L3} remains zero, suppressing loss. Conversely, in DAB2 without discharge resistance, the pulse width of the primary AC voltage v_{12} widens and the amplitude of the AC current i_{L2} also increases. The phase difference between i_{L2} and v_{12}, v_{22} is approximately 90°, and the only available power is reactive power. Even if i_{L2} increases, the amount of active power exchange can be maintained at 0% as per the command value, and only copper loss and conduction loss will increase. This is generally undesirable. The purpose of the proposed control, however, is to utilize this loss to maintain voltage balance. This is as intended. In DAB1 and DAB2, a loss of 3%, which is equivalent to the discharge resistance, occurs due to the control. Note that even if a larger disturbance occurs, i_{L2} is further increased by narrowing the pulse width of v_{22}. This maintains voltage balance by generating larger losses.

4 Postscript

We proposed voltage balance control that can be applied to DABs in ISOS connection without using any auxiliary circuits. First, we clarified that if the interchangeable power is large, the side that outputs DC power is stable. Based on this, the first control adjusts the interchange power according to the voltage imbalance for the unstable side that receives power from the DC. If only the first type of control is used, the voltage balance becomes more unstable as the interchangeable power decreases. The second action is to adjust the voltage pulse



(a) Before discharge resistor is turned ON

(b) After discharge resistor is turned ON

Fig. 8 **AC Side Waveforms at 0% Power Interchange (No Load)**

Before the discharge resistor is turned ON, the pulse width on primary side is narrowed and the current is reduced. After the resistor is turned ON, the waveforms of DAB3 with the discharge resistor do not change. While on the side of the DAB2, the pulse width on the primary side is expanded and the AC current is increased.

width on the AC side. In a DAB with insufficient DC voltage, losses are suppressed by minimizing the fundamental wave component of the AC current flowing through the high-frequency transformer. Additionally, in a DAB with excessive DC voltage, the fundamental wave component of the AC current is increased. This promotes a discharge of excessive DC voltage due to copper loss and conduction loss. In a mini-model experiment with three DABs connected in series, the effectiveness of the proposed control increased as the interchange power decreased. It is revealed that the proposed control can maintain voltage balance even under no load.

In the future, we will further evaluate the proposed control for product application. By utilizing the high-voltage DC power isolation and power flow control realized by this control method, we intend to proceed with the development of distinctive products such as rapid charging of large electric vehicles and DC power distribution in response to the higher voltages.

・All product and company names mentioned in this paper are the trademarks and/or service marks of their respective owners.

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