Static Characteristic Analysis of Proposed Bi-Directional Dual Active Bridge DC-DC Converter

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Recently, increased attention is being paid to power supply networks using energy storage devices such as batteries. Network topologies using bi-directional isolated DC-DC converters of low or medium capacity are required for the diversification of power supply networks. The dual active bridge (DAB) DC-DC converter is one of the most effective bi-directional isolated DC-DC converters. However, the circuit has some inherent problems such as degradation of power efficiency and the occurrence of surges during light-load operation. In this paper, we propose a control technique to solve these problems. From the experimental results, it is confirmed that the maximum power efficiency improvement was 16% for a light load. Applying two operation modes, the proposed operation in light load and the conventional operation in heavy load, the circuit can be operated across a full range of road. To switch between the two modes seamlessly, the precise boundary point of the two modes is needed for feedback control. Therefore, a precise static characteristic analysis with loss was carried out. From the results, the loss included simple equivalent circuit model was obtained. The root mean square error between the proposed analysis and the experimental results is within 4%.

Keywords: isolated bi-directional DC-DC converter, static characteristic analysis, dual active bridge

1. Introduction

Recently, the power supply network including battery is diversified, and the bidirectional dc-dc converter has been focused. The DAB dc-dc converter is very simple structure and one of the most popular circuits in the bidirectional dc-dc converter. Some examples are for UPS (6), for automotive (71–81) and for energy storage system (96). One of the feature is achieving zero voltage switching (ZVS) in natural operation. However, hard switching and/or power efficiency for a light load condition is the intrinsic problem (6). Some research have been done to solve the problem, for instance, use of resonant type converter with snubber circuit (71), silicon carbide (SiC) power device and new magnetic materials (86), and Quasi-ZCS operation with LC filter (95). Furthermore by applying switching modulation, DAB converter works in wide range of input voltage and load condition (60–112). These objectives of switching modulation controls are to regulate voltage and satisfy load variation (60), to expand soft switching region (103), and minimize the total power losses (109). However, the most of the researches do not concern loss components (109–115). However, to design the operation technique of DAB converter precisely, analyzing the circuit with loss components becomes important.

Therefore, in this paper, the details of the analysis using a simple analytical model, are described and confirmed with some experiments. Also, the proposed improvement technique for power efficiency and the surge problem of light-load-operation has been proposed.

In Sect. 2, it is revealed that the output power analysis for the conventional DAB DC-DC converter. In Sect. 3, intrinsic surge problem of a DAB DC-DC converter is described. In Sect. 4, the static characteristic analysis has been proposed. In Sects. 5 and 6, loss included analysis of conventional operation and proposed operation with the proposed simplified analysis technique has been described, respectively. In Sect. 7, the some experiments have been done.

2. Conventional Operation a DAB DC-DC Converter

Figure 1 shows the circuit schematic of the basic DAB dc-dc converter. Figure 2 shows the operating waveforms with
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Fig. 2. Conventional operating waveform

Fig. 3. Phasor diagram (13): (a) Forward power flow mode (light load); (b) Forward power flow mode (heavy load); (c) Reverse power flow mode

the conventional operation (14). In the conventional operation, the output power is operated by the phase-shift shown as \( \phi \) between the primary voltage \( v_P \) and secondary voltage \( v_S \) of transformer. Figure 3 shows the phasor diagram. \( V_P, V_S, V_L, I \) are phasor symbols for \( v_P, v_S, v_L, i \), respectively. When \( V_S \) is lagging \( V_P \) in forward power flow mode (Figs. 3(a) and (b)), and when \( V_S \) is leading \( V_P \), it is operated in reverse power flow mode (Fig. 3(c)).

The output power \( P_o \) can be obtained as

\[
P_o = \frac{V_{in}V_{out}}{\omega L} \left( 1 - \frac{\varphi}{\pi} \right) \tag{1}
\]

The output power can be controlled with the phase difference \( \varphi \). The waveform of the current \( i \) is changed by the load condition. In this paper, current \( i \) crossed the zero line in the state 2 is defined as a light load, and current \( i \) crossed the zero line in the state 1 is defined as a heavy load as shown in Fig. 2.

3. Intrinsic Surge Problem of a DAB DC-DC Converter

As mentioned in above, well known problem of a DAB DC-DC converter is hard switching in the light condition. However, previous researches have not been addressed about the switching surges problem.

It is caused by the reverse recovery effect of the diode. Figure 4 shows \( \varphi-P_o \). The switching surges occur for a light load range of this figure.

Figure 5 shows the generation mechanism of switching surges when \( V_{in} > V_{out} \). The surges voltage occurs in the transition from State 1 (3) to State 2 (4), repeatedly. \( C_d \) is the parasitic capacitance of diode which is connected in parallel with the ideal diode, and \( L_{wire} \) is parasitic reactance. At the light load, the diodes \( D_4 \) is conducting in State 1. Then the switch \( Q_3 \) is turned on when state changes from State 1 to State 2. At this instantaneous moment, the diode \( D_4 \) is switched from a forward bias condition to a reverse bias condition, immediately. And the switching surges are occurred with the resonance of \( C_d \) and \( L_{wire} \) due to reverse recovery phenomenon. With the same reason, when \( V_{in} < V_{out} \), the surges occurs in the transition from State 2 (4) to State 3 (1) on the primary side.

Commonly, to protect the switches from the switching surges, snubber circuit are applied. However, the power loss at the snubber circuit cannot be ignored for a light load. Otherwise, the resonant converter type is also popular, but the additional components are needed (9).

4. Proposed Operation Method

We have proposed the software-based compensation method for a basic DAB dc-dc converter topology (15) (16). It can reduce the switching surges for a light load, without any of additional circuits such as the snubber circuits or resonant circuits. Figure 6 shows idealized waveform of the proposed operating method. When \( V_{in} < V_{out} \), as it can be seen from
the waveforms, the direction of primary side current of transformer $i$ during each on-time of $Q_1$ and $Q_2$ is restricted to avoid the crossing the zero line. Due to the restriction, the zero-current-switching can be realized for $Q_1$ and $Q_2$, respectively. The ideal static analysis has been done as follows. This converter has six operational states in one switching period for each of the buck and boost mode operation, respectively. The each element is treated as ideal in equivalent circuit.

The detailed description of the ideal circuit is revealed in previous papers \cite{15,16}. Therefore, only the results are shown in this paper.

### 4.1 Buck Mode Operation for a Light Load
In buck mode, the primary side switches $Q_1$ and $Q_2$ are turned-on twice in the period. Firstly, $Q_1$ and $Q_2$ are turn-on at $t = 0$ and $T_s/2$. Secondly, they are turn-off at $t = A$ and $T_s/2 + A$. Thirdly, they are turn-on at $t = \varphi$ and $T_s/2 + \varphi$. Fourthly, they are turn-off at $t = T_s/2$ and $T_s$.

$A$ is calculated as

$$A = \frac{V_{in} - V_{out}}{V_{in} + V_{out}} \left(\frac{1}{2} T_s - \varphi\right) \tag{2}$$

### 4.2 Boost Mode Operation for a Light Load
In boost mode, the secondary side switches $Q_3$ and $Q_4$ are turned-on twice in the period. Firstly, $Q_3$ and $Q_4$ are turn-on at $t = 0$ and $T_s/2$. Secondly, they are turn-off at $t = B$ and $T_s/2 + B$. Thirdly, they are turn-on at $t = \varphi$ and $T_s/2 + \varphi$. Fourthly, they are turn-off at $t = T_s/2$ and $T_s$.

$B$ is calculated as

$$B = \frac{2V_{out}}{V_{in} - V_{out}} \varphi \tag{3}$$

### 4.3 Output Power Control for a Light Load
The ideal analysis for the both of buck and boost mode operation can be done for power. By the result of the ideal analysis, the output power $P_o$ can be obtained as

$$P_o = \frac{2X^2}{T_s L} \left| \frac{V_{in} + V_{out}}{V_{in} - V_{out}} \right| V_{in} V_{out} \tag{4}$$

In buck mode, $X = A$, and in boost mode, $X = \varphi$.

### 4.4 Output Power Control for a Heavy Load
For a light load, with the output power increasing, the periods of which all switches turned OFF ($A \sim \varphi, \pi + A \sim \pi + \varphi, B \sim \pi, \pi + B \sim 2\pi$) becomes shorter. $A$ equal to $\varphi$ or $B$ equal to $\pi$ is the boundary between light load and heavy load. Therefore, for a heavy load condition, the only conventional phase-shift operation is active. From the results, it can be seen that it is possible to control the output power seamlessly despite of the load condition. Relationship $\varphi$ and $P_o$ of conventional and proposed operation is shown in Fig. 7.

### 4.5 Pulse Generating Method
Figure 8 and Fig. 9 show the generating mechanism of proposed driving signal. As mentioned above, the gate signal is the combination of the phase shift signal and the masked signal. The mask width is
calculated and controlled by (2) and (3), respectively.

5. Loss Included Analysis of Conventional Operation

Equation (1) was for the ideal state without consideration of the conduction loss of the body diodes and switches and the parasitic resistance of the transformer. This chapter will be described analysis of static characteristics in consideration of these losses. In order to analyze and make some definitions, in the operation waveform of Fig. 2, the both of light load and heavy load can be divided into four states. To analyze the characteristics of the circuit, the Extended State-Space Averaging Method (SSA) is applied.

In order to simplify the loss analysis, the loss including the resistance of the switches and transformer is defined as $r_{loss}$. In any states, current pass through the two switches in the primary side and the secondary side. Therefore, in this circuit topology, it is possible to represent the loss resistance $r_{loss}$ with one resistor in every state. Equivalent circuits corresponding to each state in buck mode operation are shown in Fig. 10, where $\bar{v}_o$ is the low-frequency component of $V_o$.

For analysis, solving for $i_L$ and $i_c$,

for State 1 ($0 \leq t \leq DT_s$) In Fig. 10(a), voltage law of the circuit is

$$ L \frac{di_L(t)}{dt} = V_m + \bar{v}_o - i_L(t) r_{loss}, \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (5) $$

Integration of Eq. (5) is

$$ L \cdot i_L(t) = \int (V_m + \bar{v}_o) dt - r_{loss} \int i_L(t) dt + C, \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (6) $$

Linear approximation of Eq. (6) is

$$ \int i_L(t) dt = \frac{1}{2} [i_L(0) + i_L(t)] \cdot t, \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (7) $$

Using Eq. (6) and Eq. (7),

$$ i_L(t) = \frac{2 (V_m + \bar{v}_o) t}{2L + r_{loss} t} + \frac{2L - r_{loss} t}{2L + r_{loss} t} \cdot i_L(0) \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (8) $$

where $r_{loss}$ is the total loss of the circuit.

In addition, the current law is expressed as

$$ i_L(t) = -i_L(t) \frac{\bar{v}_o}{R_L}, \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (9) $$

for State 2 ($DT_s < t \leq \pi$)

The current is obtained with the same way of State 1.

$$ i_L(t) = \frac{2 (V_m - \bar{v}_o)(t - DT_s)}{2L + r_{loss}(t - DT_s)} \cdot \frac{2L - r_{loss}(t - DT_s)}{2L + r_{loss}(t - DT_s)} \cdot \left( \frac{2 (V_m + \bar{v}_o) DT_s}{2L + r_{loss} DT_s} + \frac{2L - r_{loss} DT_s}{2L + r_{loss} DT_s} \cdot i_L(0) \right) \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (10) $$

$$ i_L(t) = i_L(0) + \frac{v_o}{R_L}, \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (11) $$

In one cycle in the steady state, the current flowing through the leakage inductance is symmetrical positive-negative operation. The operation of the State 3 and State 4 is equivalent to symmetrical positive-negative to the operation of the State 1 and State 2. Therefore, the analysis was performed only for half of the cycle.

Since the two half cycles are symmetric in the conventional operation,

$$ i_L(0) = -i_L \left( \frac{1}{2} T_s \right), \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (12) $$

It is possible to determine the initial value of the circuit using the Eq. (10),

$$ i_L(0) = \frac{2 (V_m - \bar{v}_o) \cdot (2L + r_{loss} DT_s) \cdot (1 - 2DT_s) + 2 (V_m + \bar{v}_o) \cdot (4L - r_{loss} \cdot (1 - 2DT_s) \cdot DT_s)}{4L + r_{loss} \cdot (1 - 2DT_s) \cdot DT_s + 4L + r_{loss} \cdot (1 - 2DT_s) \cdot DT_s} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (13) $$

Next, deriving for the average current in the output capacitor of the State 1 and State 2. The average value of $v$ in each state is calculated with

$$ i_{Lave} = \frac{(V_m + \bar{v}_o) \cdot D T_s^2}{2L + r_{loss} \cdot DT_s} + \frac{2L - r_{loss} \cdot DT_s}{2L + r_{loss} \cdot DT_s} \cdot \frac{(V_m + \bar{v}_o) \cdot (2L + r_{loss} \cdot DT_s) \cdot (1 - 2DT_s) \cdot DT_s^2}{4L + r_{loss} \cdot (1 - 2DT_s) \cdot DT_s + 4L + r_{loss} \cdot (1 - 2DT_s) \cdot DT_s} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (14) $$

From (14), the equation can be derived as follow

$$ i_{Lave} = \frac{(V_m - \bar{v}_o) \cdot (1 - 2D) T_s^2}{2L + r_{loss} \cdot (1 - 2DT_s)} + \frac{2L - r_{loss} \cdot DT_s}{2L + r_{loss} \cdot DT_s} \cdot \frac{(V_m + \bar{v}_o) \cdot (1 - 2DT_s) \cdot DT_s^2}{4L + r_{loss} \cdot (1 - 2DT_s) \cdot DT_s + 4L + r_{loss} \cdot (1 - 2DT_s) \cdot DT_s} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (15) $$
Fig. 11. The relation of $\varphi$ and $r_{loss}$ of conventional operation

\[
(V_{in} - \hat{v}_0) \cdot (2L + r_{loss} \cdot DT_s) (1 - 2D)^2 T_s^2 + (V_{in} + \hat{v}_0) \cdot (4L - r_{loss} \cdot (1 - 2D) T_s) \cdot (1 - 2D) T_s^2 \\
\frac{4L + r_{loss} \cdot (1 - 2D) T_s} {4L + r_{loss} \cdot (1 - 2D) T_s} (2L + r_{loss} \cdot DT_s) \\
\frac{1 - 2D}{2} \cdot t_s \] 

while $\alpha = 2\omega L + r_{loss} \varphi$, $\beta = 2\omega L - r_{loss} \varphi$, $\gamma = 4\omega L + 2r_{loss} (\pi - \varphi)$, and $L = 4\omega L - 2r_{loss} (\pi - \varphi)$.

The results of static characteristics are obtained by letting $\frac{d\hat{v}_0}{dt} = 0$ (therefore $T_{\hat{v}_0} = C d\hat{v}_0/dt = 0$).

The output power $P_o$ is

\[
P_o \approx V_{in} V_o \varphi \left( 1 - \frac{\varphi}{\pi} \right) \\
\{ \frac{1}{2} \left[ (1 + \frac{\varphi}{\pi}) \left( 1 - \frac{\rho_l}{\rho_1} \right) \left( 1 - \frac{\rho_l}{\rho_1} \right) \right] \} \\
+ \{ 1 - \frac{\varphi}{\pi} \} \left[ \left( 1 - \frac{\rho_l}{\rho_1} \right) \left( 1 - \frac{\rho_l}{\rho_1} \right) \left( 1 - \frac{\rho_l}{\rho_1} \right) \right] \} .
\]

When the $r_{loss} = 0 \Omega$ in Eq. (16), it will be same as Eq. (1). Figure 11 shows the analysis result of the relation of the output power $P_o$ and $r_{loss}$ of conventional operation in the both mode. In Sect. 7, the analysis results are confirmed with the experimental results.

6. Loss Included Analysis of Proposed Operation

To analyze the characteristics of the circuit, Extended State-Space Averaging Method(17) is applied again.

The analysis has been done for each of buck mode and boost mode operation, respectively. In order to simplify the loss analysis, loss resistance is defined as $r_{loss}$.

6.1 Buck Mode Operation  Equivalent circuits corresponding to each state in buck mode operation are shown in Fig. 12, where $\hat{v}_0$ is the low-frequency component of $V_o$. $D_a = (A - 0)/T_s$, $D_b = (\varphi - \alpha)/T_s$, $D_c = (\pi - \varphi)/T_s$ in Fig. 6(a).

For ease of analysis, the calculation has been performed in a half of the switching period because of the symmetric behavior of the circuit topology.

Firstly, $i_L$ and $i_C$ are obtained as follows, for State 1 ($0 \leq t \leq A$)

\[
i_L \approx \frac{2}{2L - r_{loss}} \left( V_{in} + \hat{v}_0 \right) t + \frac{2L - r_{loss} t}{2L + r_{loss}} i_L (0) \] 

\[
i_C = -i_L - \frac{\hat{v}_0}{R_L}.
\]

for State 2 ($A \leq t \leq \varphi$)

\[
i_L = 0, \quad \frac{\hat{v}_0}{R_L} \] 

for State 3 ($\varphi \leq t \leq \pi$)

\[
i_L \approx \frac{2}{2L - r_{loss}} \left( V_{in} + \hat{v}_0 \right) t + \frac{2L - r_{loss} t}{2L + r_{loss}} i_L (0) \] 

and

\[
D_c = \frac{V_{in} + \hat{v}_0}{2L - r_{loss} D_a T_s} \] 

Hence,

\[
i_C = \frac{2}{2L - r_{loss}} \left( V_{in} + \hat{v}_0 \right) \frac{D_a T_s}{2L - r_{loss} D_a T_s} - \frac{\hat{v}_0}{R_L} \] 

The average value of $i_c$ in each state is calculated with

\[
i_{c,ave1} = \frac{1}{2} \left( V_{in} + \hat{v}_0 \right) D_a T_s - \frac{\hat{v}_0}{R_L} \] 

\[
i_{c,ave2} = \frac{\hat{v}_0}{R_L} \] 

\[
i_{c,ave3} = \frac{1}{2} \left( V_{in} + \hat{v}_0 \right) D_a T_s - \frac{\hat{v}_0}{R_L} \] 

The results of static characteristics are obtained by letting $\frac{d\hat{v}_0}{dt} = 0$. And using $D_a T_s = A$.

\[
P_o = \frac{2A^2}{T_s L} \left( V_{in} + \hat{v}_0 \right) \]
D in Fig. 13. For analysis, equation is formularized for each state in boost mode operation are shown in Fig. 6(b).

\[ \phi \]

where

\[ A = \frac{(V_{in} - V_o)(T_s/2 - \phi)}{V_o + V_o + V_m(T_s/2 - \phi)r_{loss}/L} \]  \hspace{1cm} (30)

Figure 14 shows the analysis result of the relationship of the output power \( P_o \) and \( r_{loss} \) of proposed operation in buck mode. In Sect. 7, the analysis results are confirmed with the experimental results.

### 6.2 Boost Mode Operation

Equivalent circuits corresponding to each state in boost mode operation are shown in Fig. 13. For analysis, equation is formulated for each state. \( D_a = (\phi - 0)/T_s \), \( D_b = (B - \phi)/T_s \), and \( D_c = (\phi - B)/T_s \) in Fig. 6(b).

For State 1 (0 ≤ \( t \) ≤ \( \phi \))

\[ i_L \approx \frac{2(V_{in} + v_o)t}{2L + r_{loss}T_s} \]  \hspace{1cm} (31)

\[ i_{C_o} = -i_L - \frac{v_o}{R_L} \]  \hspace{1cm} (32)

For State 2 (\( \phi \) ≤ \( t \) ≤ \( B \))

\[ i_L \approx \frac{2(V_{in} - v_o)(t - D_aT_s)}{L + r_{loss}(t - D_aT_s)} + \frac{2L - r_{loss}(t - D_aT_s)}{2L + r_{loss}(t - D_aT_s)}(D_aT_s) \]  \hspace{1cm} (33)

Fig. 13. Equivalent circuits of boost mode operation

Fig. 14. The relation of \( \phi \) and \( r_{loss} \) of proposed operation in buck mode

\[ \hat{v}\]

The results of static characteristics are obtained by letting \( dv_o/dt = 0 \), therefore

\[ P_o = \frac{2(D_aT_s)^2}{T_sL} \frac{(V_{in} + V_o)(2V_{in}V_o - V_o^2D_aT_s/r_{loss}/2L)}{(V_o - V_{in} + V_o^2D_aT_s/r_{loss}/2L)(2 + D_aT_s/r_{loss}/L)} \]  \hspace{1cm} (39)

Using \( D_aT_s = \phi \)

\[ P_o = \frac{2V_{in}^2}{T_sL} \frac{(V_o - V_{in} + V_o^2D_aT_s/r_{loss}/2L)}{(2 + V_o^2D_aT_s/r_{loss}/L)} \]  \hspace{1cm} (40)

\( B \) is calculated as

\[ B = (D_a + D_b)T_s = \frac{V_o(2 + r_{loss}D_aT_s/L)}{(V_o - V_{in} + V_o^2D_aT_s/r_{loss}/L)\phi} \]  \hspace{1cm} (41)

Figure 15 shows the analysis result of the relation of the output power \( P_o \) and \( r_{loss} \) of proposed operation in boost mode. In Sect. 7, the analysis results are confirmed with the experimental results.

### 7. Experimental Results

In order to select the value of \( r_{loss} \), we perform some experiments with the prototype circuit. The main circuit is DAB.
dc-dc converter without additional circuits like snubber circuit. We had closed-loop-operation experiments with DSP TI TMS320F28335. And, also the value of A and B are manually supplied in this experiment. Experimental parameters are shown in Table 1. Dead time of each switch is set as 1 μs.

### 7.1 Surge Reduction
Figure 16 shows the waveforms of the corrector-emitter voltage and the corrector current of the low voltage side bridge of the buck converter. Figure 16(a) shows the result of the conventional operation and Fig. 16(b) shows the result of the proposed operation.

Comparing with these results, it can be seen that 99% of voltage surges and 100% of current surges of reduction.

Figure 17 shows the waveform in boost mode. Comparing with these results, it can be seen that 90% of voltage surges of reduction and 75% of current surge of reduction could be achieved.

### 7.2 Power Efficiency
Figure 18 shows the power efficiency results for the both of the conventional and the proposed operation. It can be seen that the power efficiency of buck mode can be apparently improved by up to 16% using the proposed operation at 100 W as shown in Fig. 18(a). It can be seen that the power efficiency of boost mode can be apparently improved by up to 11% at 100 W as shown in Fig. 18(b). This improvement result is not only caused by surge reduction but also the proposed operation technique.

### 7.3 Estimating the Value of Loss
Figure 19 shows \( \varphi - P_e \) of analysis and experimental results. The value of \( r_{loss} \) for the conventional operation is for the analysis is set to 2.0 Ω. The value is the measurement result of series resistance \( r_s \) of the transformer as shown in Table 1 measured with LCR meter Agilent 4263B.

The value of \( r_{loss} \) for the proposed operation is calculated with averaged equivalent resistance with the averaged power calculation describe below.

\[
\overline{P}_{loss\_conv} \approx r_s \frac{1}{T} \int_0^T (i_{Lm(t)})^2 \, dt \quad \overline{P}_{loss\_proposed} \approx r_s \frac{1}{T} \frac{V_{in}^2 T^2}{3L^2} 
\]

Table 1. Specification of DAB Dc-dc Converter.

<table>
<thead>
<tr>
<th>Transformer</th>
<th>Symbol</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Turns ratio</td>
<td>( A )</td>
<td>1:1</td>
</tr>
<tr>
<td>2) Leakage inductance (primary-refed)</td>
<td>( L )</td>
<td>110μH</td>
</tr>
<tr>
<td>3) Series resistance (primary-refed)</td>
<td>( r_s )</td>
<td>2Ω</td>
</tr>
<tr>
<td>Converter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Rated output power</td>
<td>( P_o )</td>
<td>1kW</td>
</tr>
<tr>
<td>2) Rated input direct voltage</td>
<td>( V_{in} )</td>
<td>150V</td>
</tr>
<tr>
<td>3) Rated output direct voltage</td>
<td>( V_{out} )</td>
<td>150V</td>
</tr>
<tr>
<td>4) Switching frequency</td>
<td>( f_s )</td>
<td>20kHz</td>
</tr>
<tr>
<td>5) Absolute maximum voltage ratings of IGBT collector-emitter</td>
<td></td>
<td>600V</td>
</tr>
<tr>
<td>6) Saturation voltage of IGBT</td>
<td></td>
<td>2.5V</td>
</tr>
<tr>
<td>7) Absolute maximum current ratings of diode</td>
<td></td>
<td>30A</td>
</tr>
<tr>
<td>8) Forward voltage of diode</td>
<td></td>
<td>0.8V</td>
</tr>
<tr>
<td>9) Recovery time of diode</td>
<td></td>
<td>0.1μs</td>
</tr>
</tbody>
</table>
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\[ \text{Efficiency} = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% \]

(a) Buck mode (b) Boost mode

Fig. 18. Power efficiency: (a) Buck mode \((V_{\text{in}} = 200 \text{ V}, V_{\text{out}} = 150 \text{ V})\); (b) Boost mode \((V_{\text{in}} = 100 \text{ V}, V_{\text{out}} = 150 \text{ V})\)

\[ \phi - P_o \text{ of analysis and experimental results} \]

\[ \phi = \frac{r_v D_s T^2}{3L^2} = r_v D_s V_{\text{in}}^2 T^2 \]

where \(D\) is the conduction time ratio of switching term in no load condition and \(T\) is the half of switching term.

From the calculation results, \(r_{\text{loss}}\) of the proposed operation is calculated as the averaged equivalent resistance as

\[ r_{\text{loss}} = D^3 r_v \]

From the result of our optional experiment, \(D\) is obtained as 0.5 ohm. Therefore, the \(r_{\text{loss}}\) for the proposed operation is set as 0.25 ohm. It means that the total circuit loss of the proposed operation is suppressed to one-half of the conventional operation. This leads power efficiency improvement for a light load region. Comparing the loss including analysis and experimental results, the root mean square error was within 4\% in the both of boost mode and buck mode.

8. Conclusion

By the analysis of the circuit operation and some experiments, the validation of the proposed operation for DAB dc-to-dc converter was revealed. From the analysis, \(P_o\) can be calculated with the loss included analysis for both of the conventional and the proposed technique. The root mean square error between the proposed analysis and experimental results was within 4\%. Applying the two modes, which are the proposed operation in light load and the conventional operation in heavy load, the circuit can be operated in the full load range. The maximum power efficiency improvement was 16\% for a light load.

References

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