Surge Voltage Reduction Method for DAB Matrix Converter using Circulating Current in Whole Load Condition

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***Abstract*— This paper proposes a surge voltage reduction method by achieving zero-voltage switching (ZVS) for a matrix converter or an inverter of a dual active bridge (DAB) matrix converter with circulating current in discontinuous current mode (DCM). In traditional DAB converter, ZVS cannot be achieved including a light load condition. The duty ratio calculation for a circulating current is revealed to achieve an input power factor correction and ZVS. From the experimental results with a prototype, the ZVS operation is achieved by increasing the circulating current even zero-transmission power. In addition, the grid current distortion is lower than 5.0% at the rated power regardless of the DC voltage variation of plus or minus 20%.**

Keywords*— *Three phase AC-DC converter, Matrix converter, Discontinuous current mode

I. Introduction

In recent years, to increase the driving range of electric vehicles, the battery capacity has been increasing. An increase in the number of quick chargers installed on the ground is required. Isolated three-phase AC-DC converters are suitable for high-capacity circuit configurations such as fast battery chargers. This power converter has the capability of the power factor correction (PFC) operation and galvanic isolation between three-phase power grid and battery side. In addition, the isolated three-phase AC to DC converter is required to regulate DC voltage of the battery because the battery voltage is changed against nominal DC voltage depending on the battery condition. Generally, the isolated three-phase AC to DC converter using PWM rectifier employs a medium-frequency AC transformer in order to reduce the volume of the transformer. However, the grid-tied inductors and the DC-link capacitors limits the miniaturization of the system volume. On the other hand, the isolated AC-DC converter using a matrix converter at the grid side has been studied actively [1]-[6]. The matrix converter directly generates the medium-frequency voltage from the grid frequency voltage without a DC stage. Therefore, the bulky grid-tied inductors and DC-link capacitors are not necessary.

It has been proposed that the isolated AC-DC converter using the matrix converter works on the same principle as dual active bridge (DAB) converter [7]. The conventional control methods for the DAB converter [8]-[11] are not applied to the DAB matrix converter because the grid current must be controlled sinusoidally according to the grid voltage.

Various soft-switching methods for the DAB matrix converter have been proposed [12]-[18]. The soft switching technique is achieved by combining the switching sequence with the direction of the transformer current. The duty ratio is calculated by approximating the transformer current waveform to simplify the square waveform [16]. However, the large distortion occurs in the grid current due to the approximation error. The ZVS operation in the DAB matrix converter is achieved by completely discharging the parasitic capacitance charge of the switching device [16]. Therefore, the ZVS range is determined by the current direction, the parasitic capacitance, the dead-time period, and the instantaneous current during switching. ZVS is not achieved in the light load region because the instantaneous current of the switching device is not enough to the ZVS condition. In the conventional method, the surge voltage occurs in the matrix converter side or the inverter side in the DAB matrix converter. Therefore, the operating range is limited by the surge voltage when the margin of the rated voltage of the power device is small. On the other hand, the on-resistance of the switching device increases when the high rated voltage is applied to the DAB matrix converter.

The modulation method that calculates the duty ratio without the approximation has been proposed [17]-[18]. In this method, the suppression of the grid current and zero current switching (ZCS), and zero voltage switching (ZVS) are achieved by the circulating current in a light load [18]. However, the conduction loss increases at a heavy load due to the large circulating current.

This paper proposes the surge voltage reduction method in either the matrix converter side or inverter side by achieving ZVS in the whole load region. The original idea of this paper is that the circulating current is optimized in order to achieve ZVS regardless of AC and DC voltage amplitudes and a transition power condition. The proposed method achieves ZVS by adjusting only the minimum circulating current in the whole load condition. The ZVS operation can be selected from either the matrix converter or the inverter by the direction of the circulating current. In addition, the grid current distortion is suppressed by deriving the duty ratio considering the increase of the circulating current. From experimental results, the surge voltage is suppressed to less than 1.1 times of the rated DC voltage by the proposed method.

II. Circuit Configuration And Control Method

Fig. 1 shows a circuit consisting of a three-phase to single-phase matrix converter, an inverter, and a medium-frequency transformer. The transition power is decided by phase deference between the output voltage of the matrix converter and the inverter such as a dual active bridge converter. However, the output voltage of the matrix converter is converted from three-phase voltage. Therefore, the matrix converter voltage is changed depend on grid frequency. It is necessary only to consider from 0° to 60° of a three-phase grid voltage.

Fig. 2 shows relationship between the medium-frequency operation waveforms and the switching signals of the DAB matrix converter. The circulating current assumes zero when the matrix converter and inverter output the zero voltage. Therefore, the parasitic capacitance of the switching device is not discharged when the upper arm of the matrix converter is turned from T-phase to R-phase. The ZVS method for the matrix converter side is that the circulating current i_0 is required to be the negative direction. On the other hand, the instantaneous current is zero when S_1 turns-on after S_2 turns-off in the inverter side. The ZVS operation is not achieved to keep the charge of the drain to source voltage due to zero current. To achieve ZVS in the inverter side, the circulating current i_0 is required to be the positive direction. In other words, ZVS is achieved only for either the inverter side or the matrix converter side based on the direction of the circulating current i_0.

A. Without Circulating Current

Fig. 3 shows the output voltage of the matrix converter and the output voltage and transformer current waveforms of the inverter. The duty cycle is defined as D_a, D_1, D_2, D_b and zero voltage period D_0, respectively. The zero-voltage period D_0 means that both the matrix converter and the inverter output the zero voltage. The D_a and D_1 periods output the maximum value v_1 of line-to-line voltages. The D_2 period outputs the intermediate value v_2 of line-to-line voltages. and the D_b period outputs the zero vector of the matrix converter. Therefore, the transformer current during T_b does not contribute to the transmission power. The instantaneous transformer currents i_1, i_2, and i_3 are expressed by (1).

$$\begin{cases} i_1 = \dfrac{v_1}{L} D_a \dfrac{T_{sw}}{2} \\ i_2 = i_1 + \dfrac{v_1 - NV_{dc}}{L} D_1 \dfrac{T_{sw}}{2} \\ i_3 = i_2 + \dfrac{v_2 - NV_{dc}}{L} D_2 \dfrac{T_{sw}}{2} \end{cases} \quad (1)$$

where, T_{sw} is one switching period and L is an inductor connected in series with the transformer, which is the value converted to the primary side.

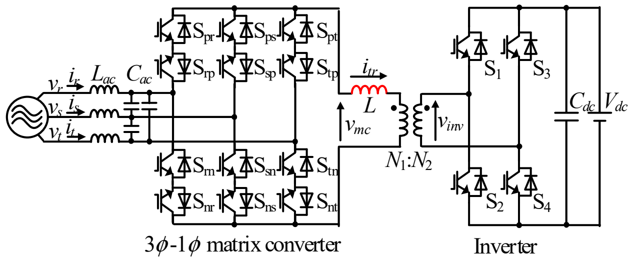
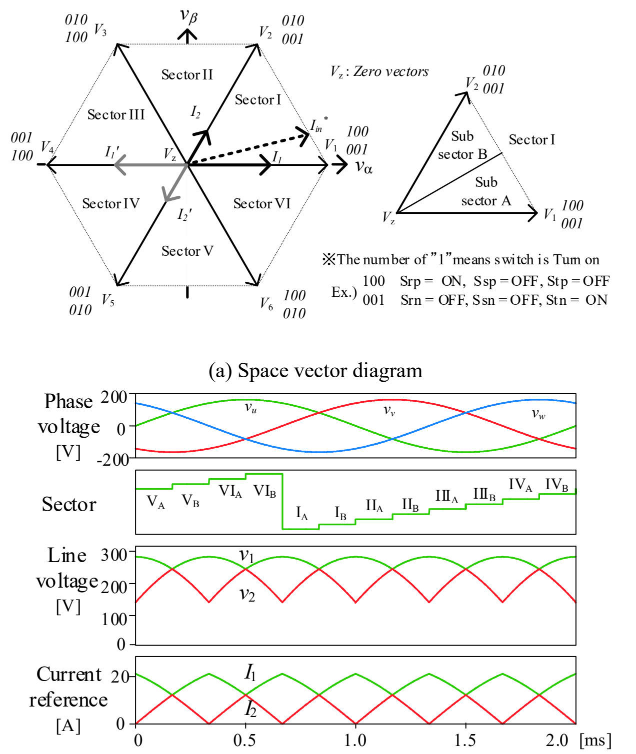


Fig. 1. Circuit configuration of isolated three-phase AC to DC converter using matrix converter.



(a) Space vector diagram

(b) Relationship between sector and reference

Fig. 2. Space vector modulation for matrix converter.

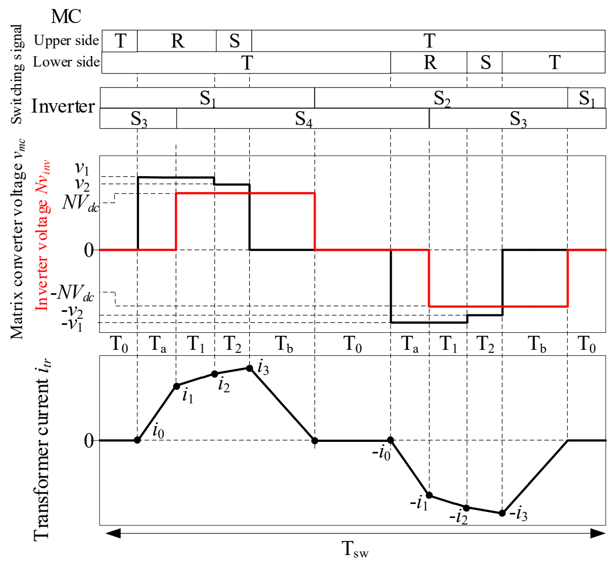


Fig. 3. Fundamental voltage vector diagram to calculate the duty for the matrix converter.

Therefore, the relationship between the current command I_1, I_2 and the duty ratio is expressed by (2) using the instantaneous value of the transformer current.

$$\begin{cases} I_1 = \dfrac{i_1}{2} D_a + \dfrac{i_1 + i_2}{2} D_1 \\ I_2 = \dfrac{i_2 + i_3}{2} D_2 \end{cases} \tag{2}$$

where, the combination of D_a and D_1 is not uniquely determined because there are no constraints. Therefore, the coefficient a is defined as the ratio of D_a and D_1.

$$a = D_a / D_1 \tag{3}$$

The coefficient a is adjusted according to the transition power and the DC voltage. From (1)-(3), each duty ratio is obtained as (4)-(7).

$$D_1 = \sqrt{\frac{4 I_1 L f_{sw}}{v_1 (a^2 + 2a + 1) - NV_{dc}}} \tag{4}$$

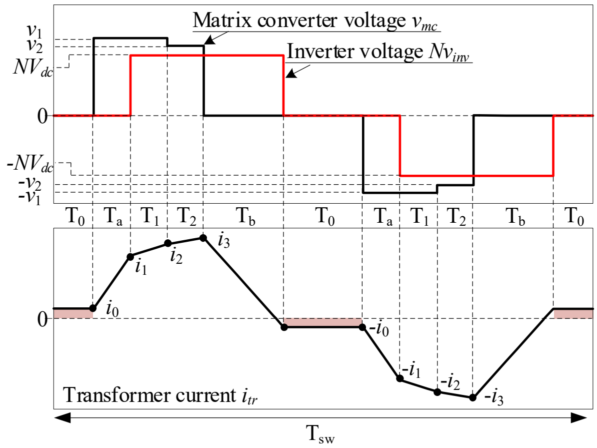
$$D_2 = \left(-b_2 \pm \sqrt{b_2^{\,2} - 4c_2}\right)\frac{D_1}{2}$$
$$\because b_2 = \frac{v_1(a+1) - NV_{dc}}{v_2 - NV_{dc}}, c_2 = \frac{I_2}{I_1}\frac{v_1(a+1)^2 - NV_{dc}}{v_2 - NV_{dc}} \tag{5}$$

$$D_b = \frac{(v_1(a+1) - NV_{dc})D_1 + (v_2 - NV_{dc})D_2}{NV_{dc}} \tag{6}$$

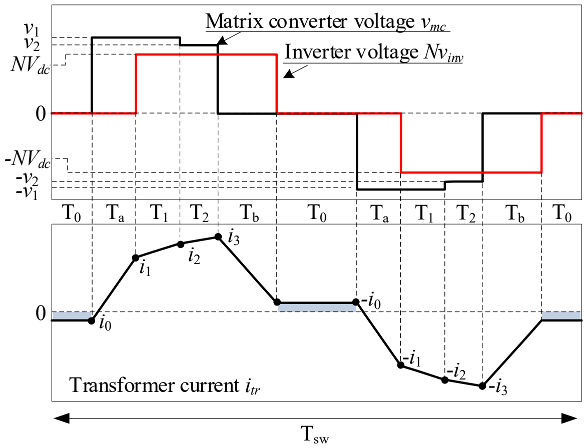
The switching pattern during T_0 to T_a for the matrix converter assumes that the commutation is from T-phase to R-phase. The drain-source voltage is not discharged by the circulating current which is almost zero when the current path in the matrix converter is changed from T-phase to R-phase. The initial current is negative to discharge the drain-source voltage in the matrix converter. However, the ZVS operation in the inverter does not achieve due to the negative initial current. The discharge of the drain-source voltage of S_1 for ZVS does not achieved when S_1 turns on after S_2 turns off. In order to achieve ZVS on the matrix converter side, the initial current i_0 needs to be negative. However, to achieve ZVS on the inverter side, the initial current i_0 must be set to positive. In other words, depending on the current direction of i_0, only one of the converters achieves ZVS. Therefore, the duty cycle for the grid current to sinusoidal is derived by considering i_0. In Chapter 2.A, the duty ratio is expressed based on the initial current of zero. In next Chapter, the initial current is considered to achieve the ZVS operation in the matrix converter or inverter.

B. With Circulating Current

Fig. 4 (a) and (b) show the operation waveforms for the initial current i_0 in the positive and negative direction. In order to superimpose the initial current i_0 on each instantaneous current, (2) is extended as (8).



(a) ZVS for inverter (i_0 : Positive)



(b) ZVS for matrix converter (i_0 : Negative)

Fig. 4. Medium-frequency voltage and current waveforms with initial current to achieve ZVS.

$$\begin{cases} i_1 = \dfrac{v_1}{L} D_a \dfrac{T_{sw}}{2} + i_0 \\ i_2 = i_1 + \dfrac{v_1 - NV_{dc}}{L} D_1 \dfrac{T_{sw}}{2} + i_0 \\ i_3 = i_2 + \dfrac{v_2 - NV_{dc}}{L} D_2 \dfrac{T_{sw}}{2} + i_0 \end{cases} \tag{8}$$

The current-time product of each period also increases or decreases depending on the initial current. Therefore, (3) is extended to equation (9) when the initial current is taken into account.

$$\begin{cases} I_1 = \dfrac{i_0 + i_1}{2} D_a + \dfrac{i_1 + i_2}{2} D_1 \\ I_2 = \dfrac{i_2 + i_3}{2} D_2 \end{cases} \tag{9}$$

Substituting (8) and (3) into (9), each duty ratio can is obtained as in (10)-(12).

$$D_1 = \frac{-b_1 + \sqrt{b_1^2 - 4b_1c_1}}{2}$$
$$\because b_1 = \frac{4Lf_{sw}(a+1)i_0}{v_1(a+1)^2 - NV_{dc}}, c_1 = -\frac{I_1}{(a+1)i_0} \quad (10)$$

$$D_2 = \frac{-b_2 \pm \sqrt{b_2^2 - 4c_2}}{2}$$
$$\because b_2 = \frac{2D_1(v_1(a+1) - NV_{dc}) + 4Lf_{sw}i_0}{v_2 - NV_{dc}} \quad (11)$$
$$\because c_2 = -\frac{4I_2Lf_{sw}}{v_2 - NV_{dc}}$$

$$D_b = \frac{(v_1(a+1) - NV_{dc})D_1 + (v_2 - NV_{dc})D_2 + 4i_0Lf_{sw}}{NV_{dc}} \quad (12)$$

Finally, the zero voltage period t_0 is defined by (13).

$$D_0 = 1 - ((a+1)D_1 + D_2 + D_b) \quad (13)$$

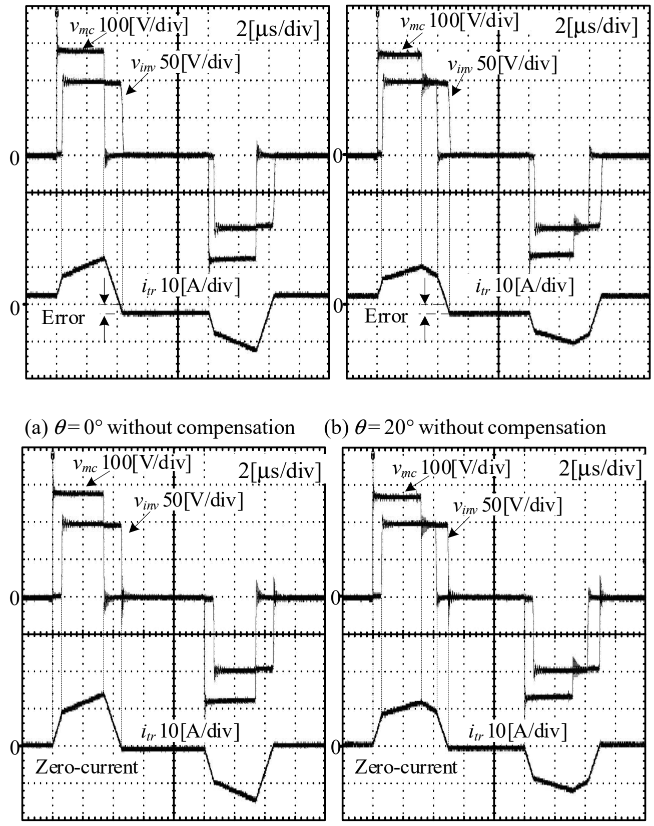
By substituting the sufficient current value for ZVS to the initial current in (10)-(13), the duty ratios are obtained to achieve ZVS in the whole load range.

III. Experimental Verification

Table 1 shows the experimental conditions. The variation of the DC voltage is assumed to be plus or minus 20% of the nominal DC voltage. The nominal DC voltage is 74V because it is the most convenient power supply voltage in our laboratory facilities. The nominal voltage can be set to 450 V by changing the turn ratio from 3.3 to 0.5 when the DC voltage range of 400 to 500 V is designed for EV applications. The effectiveness of the proposed method is not affected by the change in the DC voltage under the same boost ratio. The sum of the inductance which is connected in series with the transformer is 20 μH. The switching device of the matrix converter and inverter are SiC MOSFETs (C3M0030090K, CREE) and Si MOSFETs (IXFH220N20X3, IXYS), respectively. The turn-on and turn-off time of these switching devices are different. Therefore, the dead-time of the matrix converter and the inverter is also different. The switching devices of the inverter are connected to parallel because the high RMS current occurs at the low DC voltage. The input current distortion and the surge voltage of the matrix converter side and the inverter side are evaluated.

TABLE I. Experimental condition.

Element		Symbol	Value
Rated power		P	5 kW
Three-phase AC voltage		v_{ac}	200 V
Nominal DC voltage		V_{dc}	74 V
Grid frequency		f	50 Hz
Carrier frequency		f_{sw}	50 kHz
Leakage inductance		$L(\%Z_L)$	20 μH(94%)
Turn ratio of transformer		$N_1{:}N_2$	3.3:1
LC filter	Grid side	$L_{ac}(\%Z_{Lac})$	190 μH(0.8%)
	Grid side	$C_{ac}(\%Y_{Cac})$	15 μF(3.8%)
	DC side	L_{dc}	4.4 μH
	DC side	C_{dc}	3 mF
Dead-time	Matrix converter	T_{mc}	250 ns
	Inverter	T_{inv}	400 ns



(a) θ= 0° without compensation (b) θ= 20° without compensation

(c) θ= 0° without compensation (d) θ= 20° without compensation

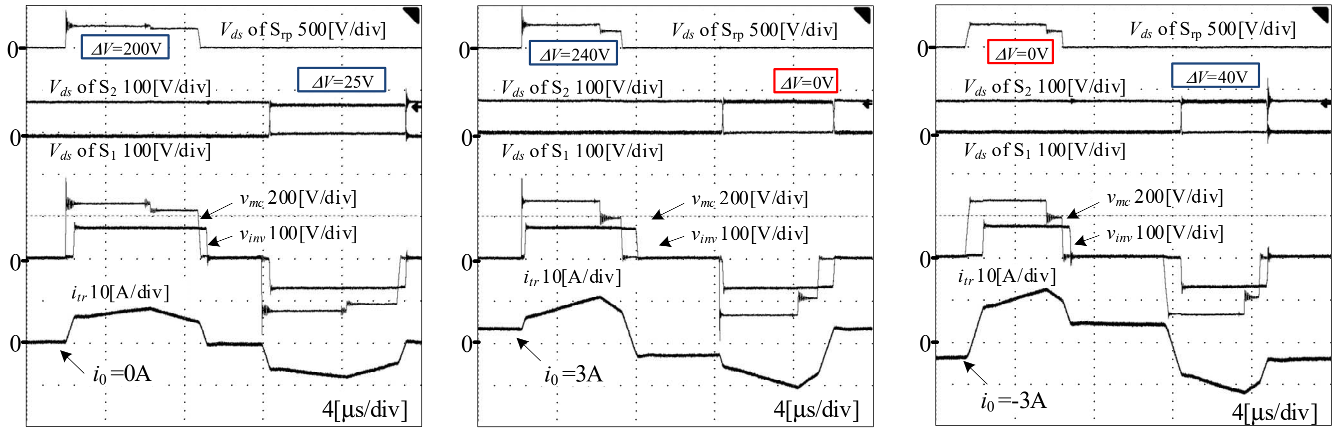
A. Dead-time Compensation

Fig. 5 (a), (b) shows the operation waveforms without the dead-time compensation on the phase angle θ=0° and 20°. The phase angle 0° is defined as the phase angle when the line-to-line voltage v_{uv} is maximum. The duty ratio for the three-phase isolated AC to DC converter using the matrix converter is calculated by (4) to (6) with the initial current of zero. However, the amplitude of the transformer current is clamped by 2 A during the zero voltage period T_0 even though the initial current of zero. The dead-time compensation is implemented to eliminate the current error which is caused by the dead-time error.

Fig. 5(c), (d) shows the operation waveforms with the dead-time compensation. The dead-time error is compensated by adding or subtracting the dead-time T_{mc} of the matrix converter to the duty ratio T_a because the amount of the dead-time compensation is constant regardless of the phase angle. The amplitude of the transformer current becomes zero during the zero voltage period to apply the dead-time compensation. In the following sections, experimental results with the dead-time compensation are presented.

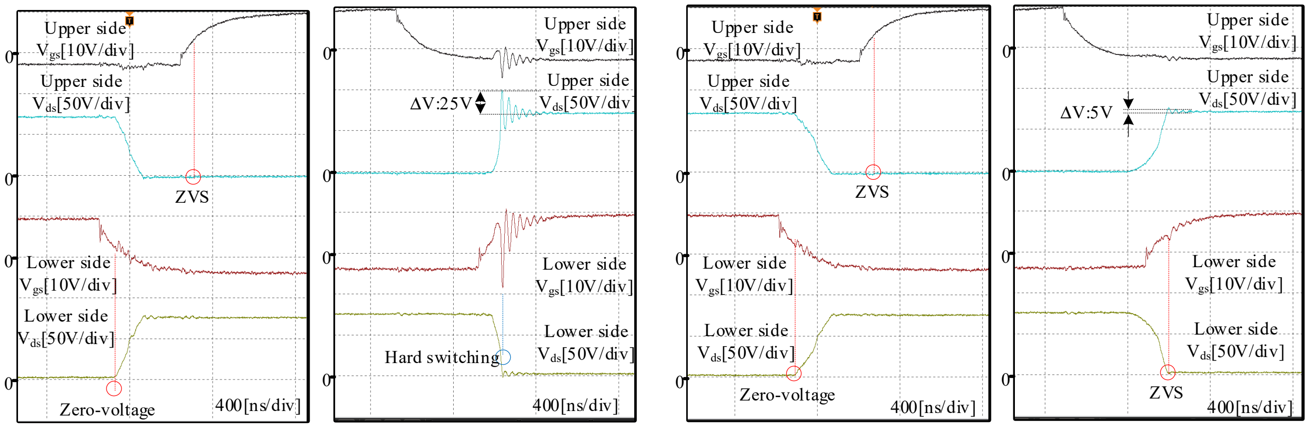
B. Surge Voltage Reduction by Circulating Current

Fig. 6 shows the drain-source voltage V_{ds}, matrix converter output voltage, inverter output voltage of the switching devices S_1 and S_2 on the inverter side and S_{rp} on the matrix converter side at 1 kW (0.2p.u.). The transformer currents during the zero-voltage period are clamped at each circulating current with any current command of 0A, 3A, and -3A. When



(a) Hard switching of both converter (i_0= 0A) (b) ZVS of inverter (i_0= 3A) (c) ZVS of matrix converter (i_0= -3A)

Fig. 6. Comparison of surge voltage at matrix converter and inverter by changing initial current i_0.



(a) Conventional method (i_0= 0A) (b)Proposed method (i_0= 3A)

Fig. 7. Zero voltage switching by circulation current i_0.

the conventional circulation current is 0 A, the surge voltage generated at the drain-source voltage of S_2 on the inverter side is 25 V, which is about 1.3 times higher than the rated DC voltage. The surge voltage of the switching devices on the matrix converter side is 200V. These are caused by the hard switching due to the lack of the instantaneous current to discharge the drain source-voltage. The recovery current flows and the surge voltage is generated due to this hard switching.

Fig. 6 (b) shows the operation waveforms with the positive direction of the circulating current (3 A). The surge voltage of S_2 is suppressed by achieving ZVS when the drain-source voltage of the switching device is completely discharged by the circulating current in the inverter side. On the other hand, the surge voltage in the matrix converter side increases from 200 V to 240 V because the instantaneous current at turn-off is increased by the circulating current.

Fig. 6 (c) shows the surge voltage with the negative direction of the circulating current (-3 A). The surge voltage generated at S_{rp} is suppressed to achieve ZVS at the matrix converter side. On the other hand, the surge voltage generated on the inverter side increases from 25V to 40V. Next section, the surge voltage and efficiency are evaluated when ZVS is achieved on the inverter side with the initial current of 3A.

Fig. 7 shows the gate-source and the drain-source voltage waveforms of S_1 and S_2 when these switches turn-on and turn-off, respectively. The transformer current is equal to the circulating current when the transition power reference is zero. The surge voltage occurs at the switching device S_1 in the upper side under zero initial current. On the other hand, the surge voltage of S_1 is suppressed by the circulating current of 3 A even though no-load state.

C. Converter Characteristics

Fig. 8 shows the relationship between the transmission power and the surge voltage generated at S_1 normalized by the rated DC voltage. In the DAB matrix converter, the drain-source voltage is completely discharged by the circulating current in the heavy load condition. However, the instantaneous current is not enough to the ZVS condition in the light load condition. In the proposed method, the circulating current is not changed by the transition power and the AC and DC voltage amplitudes. Therefore, ZVS is achieved in the whole load condition by setting the circulating current to 3A for ZVS of the inverter side. Figure 5(b) shows the efficiency characteristics when the circulating current is set to 0 A and 3 A. The proposed method achieves ZVS of the inverter side. However, the RMS value of the transformer current increases to increase the circulating current by applying the proposed method. The efficiency characteristic in the light-load is equal to or higher than that of the conventional method.

Fig. 9 shows the efficiency characteristics under the rated DC voltage. The co-efficient a which is decided by (3) is changing based on the transition power. Here, the maximum transmission power is determined by the coefficient a. Therefore, it must be changed appropriately according to the load. The optimization for coefficient a does not discuss to improve the converter efficiency in this paper. In this paper, the efficiency characteristics were obtained by varying the coefficient a from 0 to 2. The maximum efficiency of 96.0% was achieved when $a = 0.2$.

Fig. 9(b) and 9(c) show the transformer current waveforms for $a = 0.2$ and 2, respectively. The transmission power is the same at 0.2 p.u. (1 kW). The duty ratio D_a increases with the coefficient of 2 compared to 0.2. Therefore, the increase in the current peak value causes the conduction loss to increase. By selecting the optimum ratio according to the transmission power, the envelope of the largest part of the efficiency characteristics shown in Fig. 9(a) is assumed to be the efficiency characteristics of the circuit under consideration.

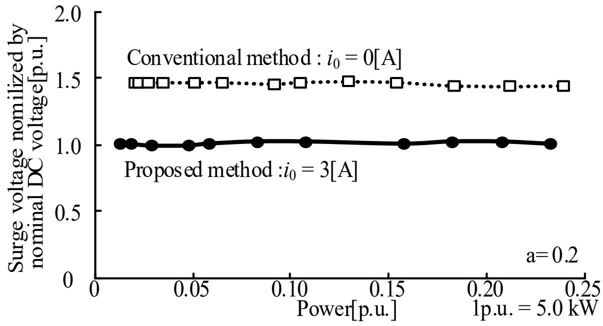
Fig. 10(a) and 10 (b) show the efficiency and THD characteristics under the DC voltage up to 20% at the rated power 5-kW. Assume that the battery is connected to the load, the efficiency and THD characteristics of the isolated three-phase matrix DAB AC-DC converter are evaluated when the DC voltage changes by plus or minus 20% against the nominal DC voltage. The DC voltage is generated by a DC power supply (PSB 9000 3U, EA - Elektro Automatik GmbH & Co. KG). It is evaluated up to the maximum transmission power at each voltage condition.

The maximum transmission power varied with the DC voltage could be transmitted at the 0.9 p.u. of rated power. The system efficiency at the low voltage is lower than one at nominal voltage because the RMS current at the secondary side increases. The current distortion was suppressed to less than 5.0% at the rated power of 0.4 p.u. or more, regardless of the DC voltage.

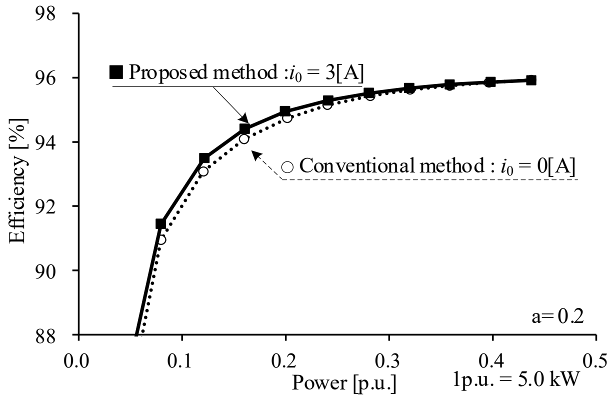
The suppression of the grid current distortion and ZVS are achieved simultaneously in whole load regions. Therefore, the usefulness of the proposed surge voltage reduction method is demonstrated. In addition, the isolated three-phase matrix AC-DC converter using the matrix converter with the proposed method is operated under a wide DC voltage range which is achieved by the buck-boost and boost operation.

IV. Conclusions

In this paper, the ZVS method using the circulating current is proposed to reduce the surge voltage in either the matrix converter side or the inverter side. ZVS of the inverter side or the matrix converter side is selected by the direction of the circulating current. Therefore, the surge voltage is suppressed to less than 1.1 times of the rated DC voltage. Furthermore, the grid current THD is suppressed to less than 3.0% from the duty ratio calculation considering the increase of the circulating current for ZVS.

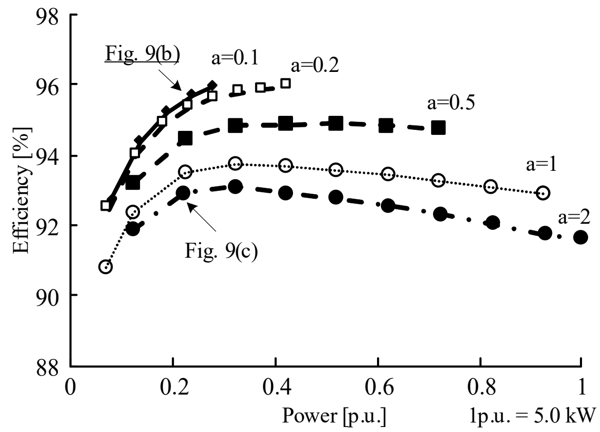


(a) Surge voltage characteristics

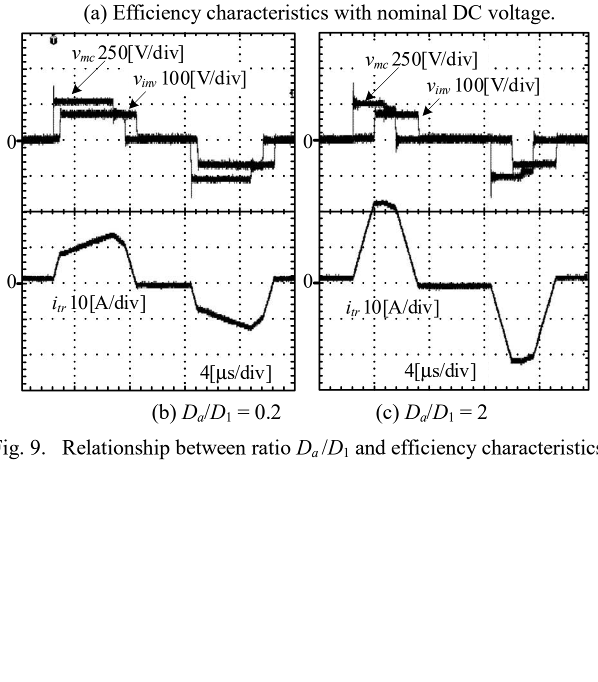


(b) Efficiency characteristics

Fig. 8. Evaluation results of characteristics with each initial current.



(a) Efficiency characteristics with nominal DC voltage.



(b) $D_a/D_1 = 0.2$ (c) $D_a/D_1 = 2$

Fig. 9. Relationship between ratio D_a/D_1 and efficiency characteristics.

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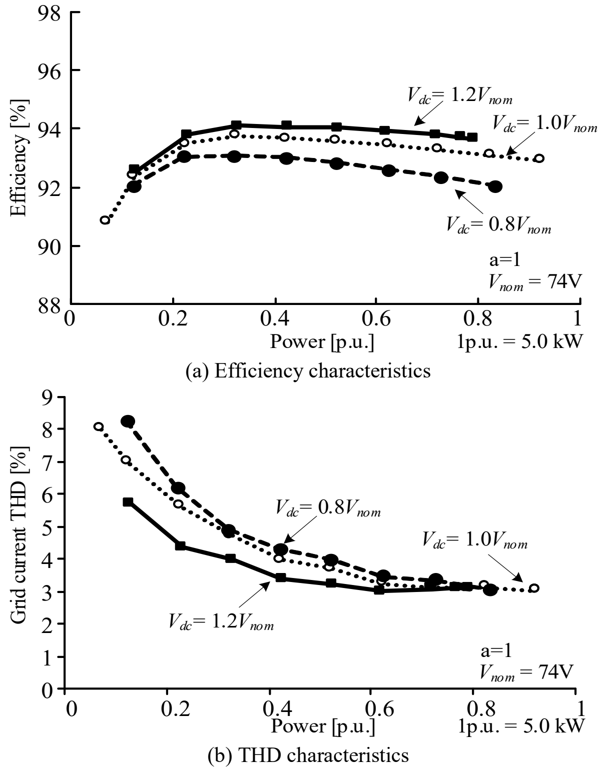

Fig. 10. Efficiency and THD characteristics with DC voltage variation of plus or minus 20%.

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