Downsized and High Efficient Direct Power Converters for High-power Servo Application

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***Abstract-* This paper proposes to apply an AC/AC direct converter topology for servo systems. In the conventional AC/AC converter which consists of a PWM rectifier and a PWM inverter, the p-n junction temperature becomes high at the low output frequency or the servo-lock operation because the output current concentrates at the specific switching devices in the inverter. On the other hands, the AC/AC direct converter such as matrix converter is able to reduce the junction temperature of the switching devices. In this paper, the junction temperature of each type of the converters is evaluated by using the thermal simulation of the p-n junction. The output frequency of the conventional matrix converter and the indirect matrix converter are 1/8 and 1/2 smaller compared to the conventional AC/AC converter when the same temperature ripple is obtained in low output frequency region. That is, when these converters use the same current rating device, the matrix converter can operate at a frequency lower than the conventional AC/AC converter.**

I. INTRODUCTION

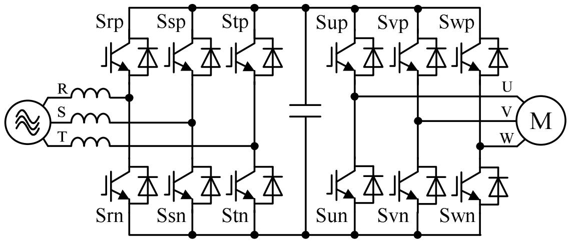
Recently, conventional AC/AC converters, such as the Back-to-Back converter [1] which consists of a rectifier, an inverter and a large electrolytic capacitor have been actively used for high power servo amplifier applications. The Back-to-Back system can convert an AC power supply voltage into an AC voltage of variable amplitudes and frequencies with good input current waveform.

Servo applications require a large torque at the low speed or servo-lock operation. The requirement of starting torque may be reached to 400% of rating torque. In this situation, the output current concentrates at the specific switching devices in the inverter. The p-n junction temperature of the switching device rises remarkably. Since the current rating of the switching device is constrained by the junction temperature. Consequently, the practical inverters limit the output frequency or use larger current rating switching devices. The use of a large current rating device increases the cost and the size of the converter. Other than that, the electrolytic capacitor in the dc link part of the inverter is also a high cost and bulky device.

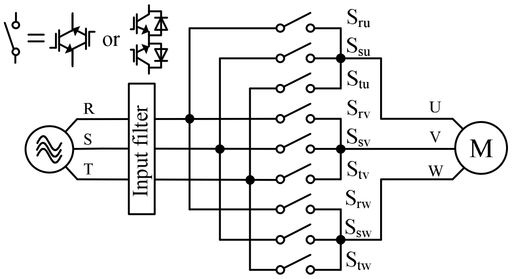
Matrix converters that can directly convert an AC power supply voltage into an AC voltage of variable amplitudes and frequencies without large energy storage have been actively investigated [3-11]. These matrix converters have advantages of high efficiency, long lifetime and downsizing in comparison to a conventional AC/AC converter. In addition, the matrix converter can avoid rise of temperature of the switching devices at the low output frequency operation. Therefore, the matrix converter is suitable for low frequency application such as the high-power servo application.

There are two circuit topologies of the matrix converter. The first one is so called 9-switches matrix converter or conventional matrix converter, which place 9 ac switches on the grid and there is no dc link part in this topology. The conventional matrix converter has no problem in terms of the current concentration at the low frequency output because the load current flows in different switching devices according to the input frequency.

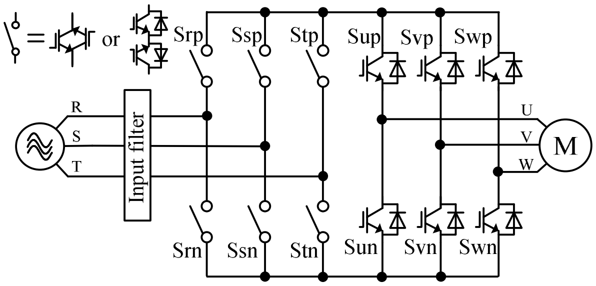
The second one is so called indirect matrix converter which connects a current type rectifier to a voltage type inverter without a dc capacitor. The indirect matrix converter is suitable for parallel connection of the inverter parts in servo application because the indirect matrix converter has the dc part. The



(a) Conventional AC/AC converter.
(Back to Back converter)



(b) Conventional matrix converter.



(c) Indirect matrix converter.
Figure 1. Circuit topologies.

inverter stage able to reduce the switching loss by adopting the zero voltage switching for the inverter stage devices. Therefore, the indirect matrix converter can also reduce the rise of temperature in the inverter stage devices.

This paper evaluates the rise temperature at the p-n junction of switching devices at the low output frequency operation among the conventional AC/AC converter and the matrix converters. At first, the conventional back to back converter and behavior of P-N junction temperature are introduced. Next, the principles of the matrix converters and the control methods are described. In particular, the control method for the indirect matrix converter is proposed to reduce the junction temperature of the inverter part. Finally, the simulation results regarding the junction temperature are shown to indicate the validity of the direct converter.

II. CONVENTIONAL AC/AC CONVERTER

Figure 1 shows the conventional AC/AC converter that is so called the back to back (BTB) converter. This converter consists of a voltage source rectifier and a voltage source inverter. The output voltage and input current of each converter is controlled by auto current regulators and an auto voltage regulator as referred as in [2].

When the inverter outputs low frequency with large current, the load current concentrates on a part of the switching device. The p-n junction temperature of the switching device follows this current and results a rapidly increment and the temperature ripple occurs according to the output frequency. The temperature ripple in the semiconductor chip gives stress to the bonding wires, and solder layers in the power module. Therefore, a large temperature ripple will affect the lifetime and reliability of the component.

The output frequency or the maximum current at the low frequency region is limited in order to suppress the temperature ripple. The current rating of the switching device is decided by the low output frequency condition according to the applications. Then, the large current rating device is chosen for low speed with high torque application such as elevator or servo system. That is, the current rating of the switching device in the power converter is different depending on the minimum output frequency even if the rated power at the rated speed is the same. It is noted that the input frequency is a constant along with the voltage supply frequency, thus the current does not concentrate on specific device in the rectifier stage.

III. CONVENTIONAL MATRIX CONVERTER

Figure 1(b) shows the conventional matrix converter using 9 bi-directional switches. The bi-directional switch is constructed by a conventional IGBT with a series diode or a reverse blocking IGBT [10]. The matrix converter generates output voltage by chopping the ac input voltage directly. Besides, the input current is controlled at the same time. That is, the matrix converter has no input current harmonics components.

The conventional matrix converter has four main advantages in comparison with the BTB converter;

1) Smaller size due to no large energy storage.

2) Longer life-time because of no electrolytic capacitor. Then, the matrix converter can abbreviate the period of regular maintenance.

3) High efficiency conversion because of only one switching device passing through between the power grid and the load.

4) No load current concentration on the switching device. When the power converter outputs dc current (servo-lock condition), this output current flows into three switching devices which is alternated by the input frequency. However, for the BTB converter, the output current flows into only one switching device. Therefore the thermal duty of the conventional matrix converter is much lower than the inverter of a BTB converter. For this reason, the conventional matrix converter does not use the large current rating device in comparison with the BTB converter because the peak of the p-n junction temperature is small.

The input voltage for the conventional matrix converter shown in figure 1(b) is $[v_r, v_s, v_t]^t$ and the output voltage is $[v_u, v_v, v_w]^t$. The relations between the input voltage and the output voltage can be expressed as

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \begin{bmatrix} s_{ru} & s_{su} & s_{tu} \\ s_{rv} & s_{sv} & s_{tv} \\ s_{rw} & s_{sw} & s_{tw} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \qquad (1)$$

where the switching function s is defined as s=1 means the switch S is turned on, s=0 means the switch S is turned off.

In this paper, the conventional matrix converter is controlled by the virtual AC/DC/AC conversion [7]. This method independently controls the input side and output side while considering it is a a virtual rectifier and inverter system.

IV. INDIRECT MATRIX CONVERTER

Figure 1(c) shows a typical configuration of an indirect matrix converter. This converter consists of a current type rectifier and a voltage type inverter. It should be noted that the indirect matrix converter does not use boost up reactors because the rectifier stage uses the current type rectifier.

The difference to the BTB converter is that the indirect matrix converter has no capacitor in the dc link part. Therefore, the indirect matrix converter can achieve downsizing and high reliability as the same as the conventional matrix converter.

The advantage of this circuit over than the 9-swiches matrix converter is to have an easy circuit structure. The indirect matrix converter can use the conventional power IGBT module for the inverter side including the gate drive units. Furthermore, the indirect matrix converter is suitable for the applications that require dc common connection and dc energy storage such as battery or EDLC [8].

The output voltage controller affects the input current controller although the indirect matrix converter is divided into the inverter stage and the rectifier stage. The relations between the input voltage and the output voltage can be expressed as

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \begin{bmatrix} s_{up} & s_{un} \\ s_{vp} & s_{vn} \\ s_{wp} & s_{wn} \end{bmatrix} \begin{bmatrix} s_{rp} & s_{sp} & s_{tp} \\ s_{rn} & s_{sn} & s_{tn} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \tag{2}$$

where the switching function s is defined as s=1 means the switch S is turned on, s=0 means the switch S is turned off.

The switching function is important to consider the influence between the input and output stage. The output voltage is changed by the switching function from the inverter stage but also the rectifier stage.

In order to obtain high efficiency, zero current switching is implemented in the indirect matrix converter. The rectifier part switches during zero vector period of the inverter part. Since the dc link current becomes zero during the zero vector, there is no switching loss occur to the rectifier part. Therefore, the indirect matrix converter achieves higher efficiency than the BTB converter [8].

However, when the inverter outputs low frequency with large current, the load current concentrates on a part of the switching device because the converter consists of the inverter stage that is same as the BTB converter. Therefore, we propose a new control scheme for the indirect matrix converter to solve the current concentration problem.

In the proposed control scheme, the switching of the inverter part is performed while the rectifier stage output the zero vector, where each of the rectifier phase arm (Srp, Srn) or (Ssp, Ssn) or (Stp, Stn) are turned on. That is, zero voltage switching is applied in the inverter stage. As a result, the rise of temperature at the inverter stage can be decreased because no switching loss occurs in the inverter stage. Additionally, high efficiency is also obtained in the indirect matrix converter. In this paper, the control strategy for the indirect matrix converter is referred in [9].

V. EXPERIMENTAL AND LOSS AND THERMAL ANALYSIS

A. *Experimental result*

Figure 2 shows the input current and the output current waveforms of the indirect matrix converter using the proposed method [9]. The input voltage and input current demonstrates that unity factor is obtained by the proposed method. Further, good sinusoidal waveforms are obtained for the input and the output waveform. It should be noted that the output voltage is observed by using a low-pass filter of 1 kHz cut-off frequency to monitor the low frequency component distortion.

The proposed method shows the output characteristics similar to the conventional AC/AC converter and the conventional matrix converter.

B. *Loss analysis of the switching devices*

The aim of this simulation is to confirm the decrement of the loss in the switching devices. The simulations are demonstrated by PSIM (*Powersim Technologies Inc*) with the original Digital Dynamic Library (DLL) as described in [11].

The parameters of the switching devices (Fuji Electric 2MBI50N-060) are referred to datasheets in [12]. The reverse blocking IGBT is referred in [10].

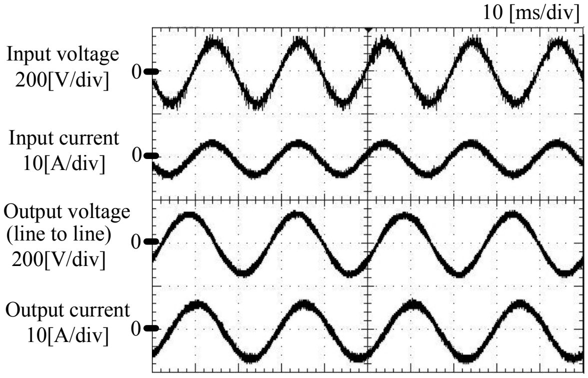


Figure 2. Steady state operation of IMC.
(Output frequency :40Hz)

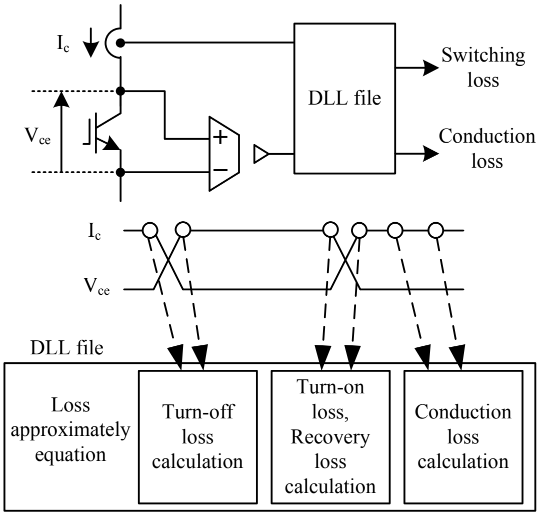


Figure 3. Principle of loss calculation method.

Table 1. Simulation parameters.

Simulation condition	
Input voltage	200 [Vrms]
Input frequency	50 [Hz]
Input power factor command	1
Carrier frequency	10 [kHz]
Output power	1 [kW]
Output frequency	50 [Hz]
Commutation time	0 [us]

Figure 3 shows the configuration for the loss calculation method. The instantaneous values of the current and the voltage at the switching timing are captured to the DLL. According to the collector-emitter voltage and corrector current, the power loss of the switching device is obtained by the V-I characteristic and the switching loss characteristic in the datasheet. The conduction loss and the switching loss are calculated in the DLL.

Figure 4 shows the loss analysis and the simulation parameters are shown in Table 1. The BTB system obtains efficiency of 96.3%, the conventional matrix converter obtains efficiency of 98.5%, and the indirect matrix converter obtains the efficiency of 96.9%. It should be note that the simulation

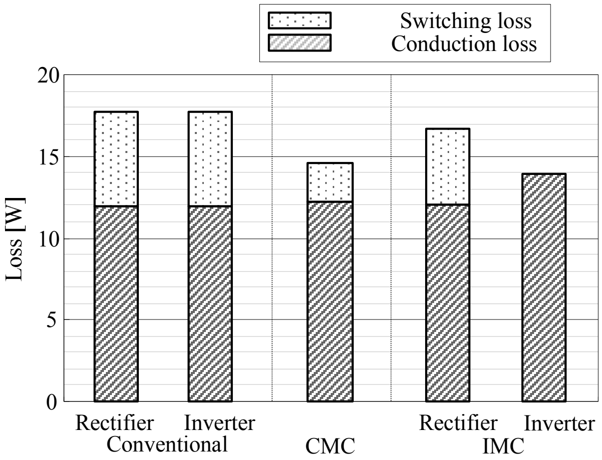
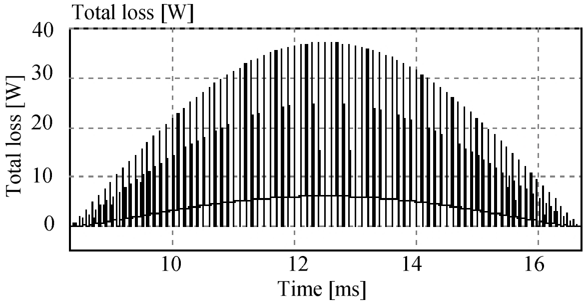
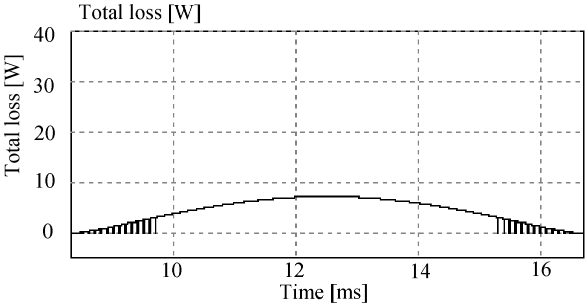


Figure 4. Power loss simulation results (Output power: 1kW).



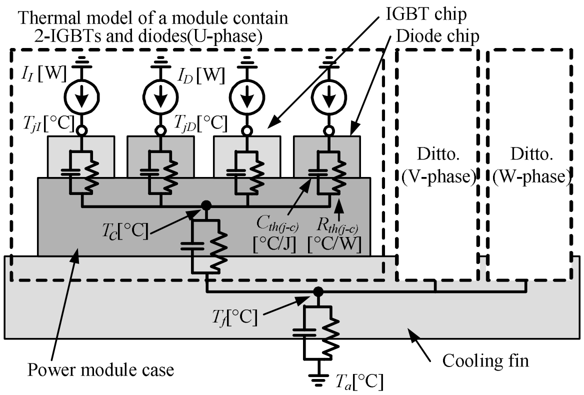
(a) Conventional AC/AC converter.



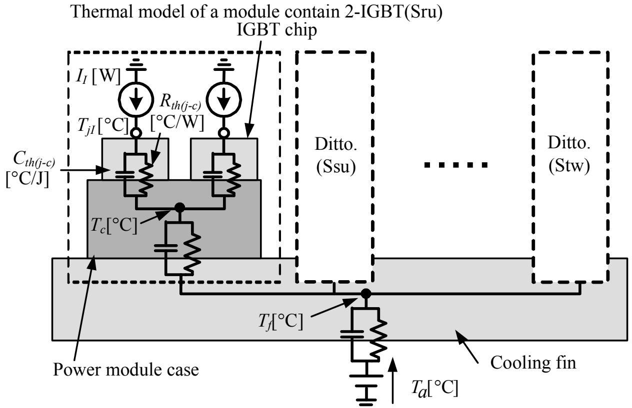
(b) Indirect matrix converter.
Figure 5. Instantaneous loss of the IGBT.

did not include the loss of the boost up inductor, which is necessary for the conventional AC/AC converter in a practical structure. Consequently, the efficiency of the conventional AC/AC converter is lower than the shown result. In the matrix converter, since only one switching device is connected between the input terminal and the output terminal, the power loss can be greatly reduced. In the indirect matrix converter, the switching loss of the inverter part becomes zero due to the zero voltage switching. Therefore, a higher efficiency is achieved than the BTB converter.

Figure 5 shows the instantaneous loss of the IGBT in the inverter side. The conduction loss and the switching loss in the inverter are generated in the BTB converter as shown in Figure 5(a). In contrast, there is only conduction loss at the inverter of the indirect matrix converter as shown in figure 5(b).



(a) The inverter side.of BTB and IMC.



(b) Conventional matrix converter.
Figure 6. Thermal analysis model.

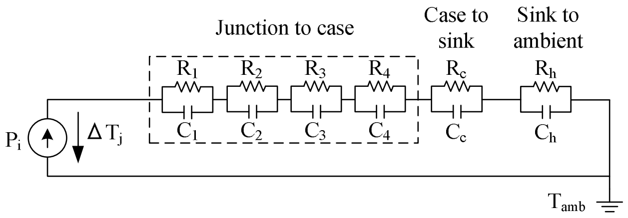


Figure 7. Thermal analysis model.

Table 2. Thermal resistance and capacitance.

	1	2	3	4
Ri [℃/W]	0.0038	0.1510	0. 3181	0.0428
Ci [J/℃]	0.2614	0.0662	0.3144	23.3499
Rd [℃/W]	0.0813	0.2619	0.8570	0.1578
Cd [J/℃]	0.0123	0.0381	0.1167	6.3366

C. *Thermal analysis of the switching devices*

Figure 6(a) shows the thermal analysis model for the inverter stage in both the BTB converter and the indirect matrix converter. Figure 6(b) shows the thermal analysis model for the conventional matrix converter. In figure 6, R_{th} is the thermal resistance and C_{th} is the thermal capacity. I_I and I_D are the equivalent current source of the instantaneous loss of the IGBT and the diode, respectively. In addition, the IGBTs and the diodes are packaged in one module for each phase (U, V, W), respectively. Those modules are put on a cooling fin. The ambient temperature T_a was set to 25 °C.

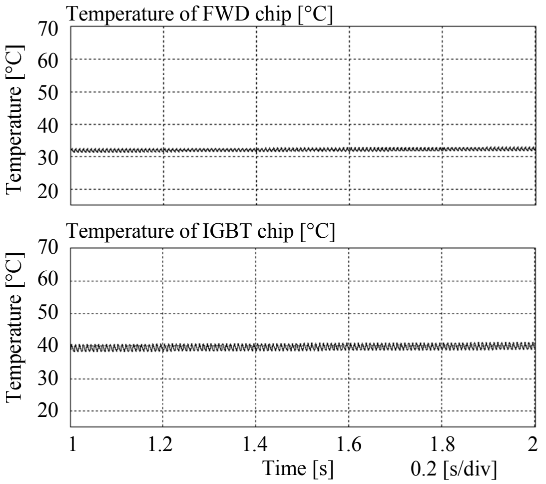
Fig. 7 shows the transient thermal resistance and the thermal capacity from the p-n junction to the case, which are expressed by fourth order model using four resistors and four capacitors. Thermal simulation of the p-n junction is implemented to evaluate the conventional matrix converter and the indirect matrix converter. Using this model, the junction temperature of the diode (T_{jD}) and IGBT (T_{jI}) are obtained.

Each parameter in the thermal model is obtained from of the transient thermal resistance characteristic using least square method [10].

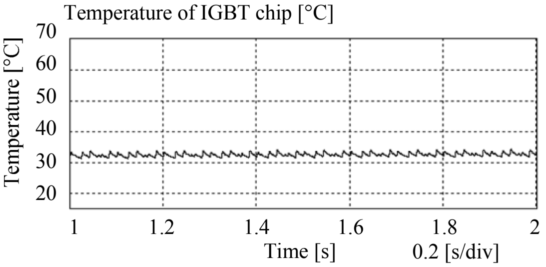
$$R_{th(j-c)} = \sum_{n=1}^{4}\left\{R_n \cdot (1-\exp\frac{-t}{R_n \cdot C_n})\right\} \qquad (8)$$

Table 2 shows the parameters of transient thermal resistance and capacity from junction to case in experimental system. R_i and C_i are the parameters of the IGBTs, R_d and C_d are the parameters of the diodes.

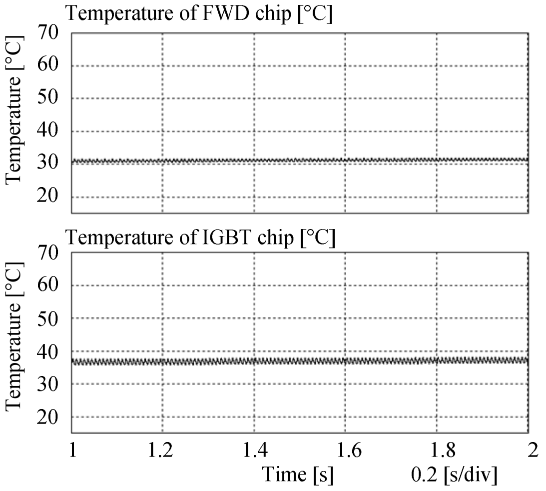
Figure 8 and figure 9 show the simulation results of the thermal analysis for each topology at the output power is 7kW. When the output frequency is high, the peak temperature and



(a) Conventional AC/AC converter.

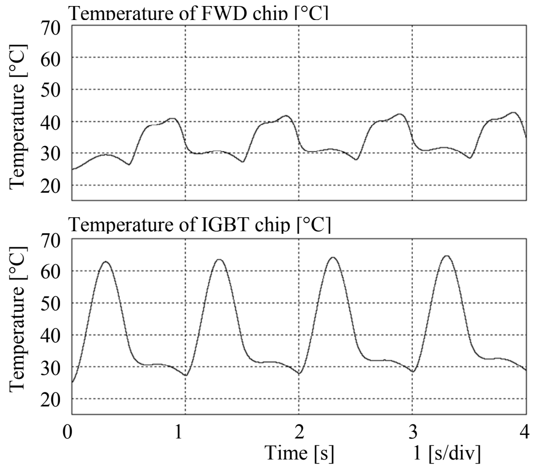


(b) Conventional matrix converter.

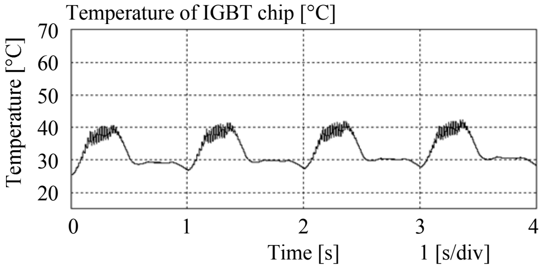


(c) Indirect matrix converter.

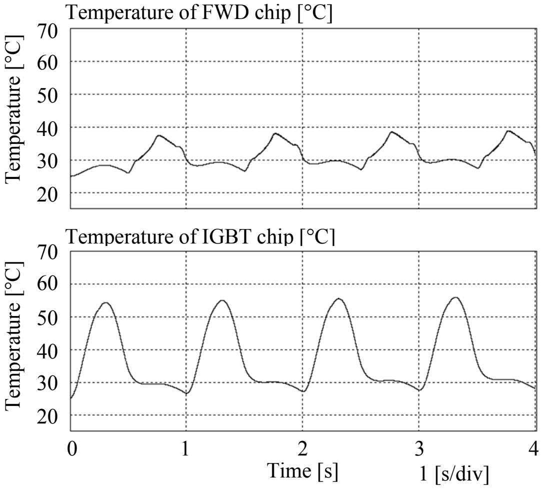
Figure 8. Junction temperature of the IGBT and diode.
(Input frequency: 50Hz, Output frequency: 120Hz)



(a) Conventional AC/AC converter.



(b) Conventional matrix converter.



(c) Indirect matrix converter.

Figure 9. Junction temperature of the IGBT and diode.
(Input frequency: 50Hz, Output frequency: 1Hz)

the variation temperature becomes low as shown in figure 8 because the output frequency is much higher than the cut off frequency of the transient thermal resistance.

On the other hand, when the output frequency is low, the junction temperature of the diode chip and the IGBT chip are gradually rise in a pulsating according to the output frequency because the output current concentrates at the specific switching device for long time.

In the conventional matrix converter, the temperature behavior is oscillated because the current flows into the switching device is dominated not only the output frequency 1Hz but also the input frequency 50Hz.

The temperature ripple in the conventional matrix converter decreases approximately 55 % of that of the BTB converter. In the indirect matrix converter, the temperature ripple decreases about 25 % of that of the BTB converter.

Figure 10 shows the relationship between the inverter output frequency and the junction temperature ripple of the IGBT chip. According to the increment of the output frequency, the temperature ripple of the chip reduces because the thermal transient response is slower than the output frequency. From figure 10, the output frequency of the conventional matrix converter and the indirect matrix converter is 1/8, and 1/2 smaller than the BTB converter when the same temperature ripple is obtained in low output frequency region. That is, the conventional matrix converter can output the low frequency which is 1/8 times smaller than the BTB converter under the same condition. The indirect matrix converter can output the low frequency that is 1/2 times smaller than the BTB converter under the same condition. In addition, the maximum temperature of the matrix converters is lower than the BTB converter. As a result, under the same output frequency for the same application, the matrix converter can use a smaller IGBT chip. These advantages become much pronounced in low speed and high torque applications such as servo system.

VI. Conclusion

This paper discussed and evaluated the conventional matrix converter and the indirect matrix converter by simulating the p-n junction thermal of the switching devices under the low output frequency operation. The simulation results are obtained as follows;

i) The conventional matrix converter can output a low frequency that is 1/8 times smaller than the BTB converter, if the same device is applied to the converter. Similarly, the indirect matrix converter can output a low frequency that is 1/2 times smaller than the BTB converter.

ii) The matrix converters can use a smaller size device in comparison with the BTB converter, provided that these two converters output the same frequency since the matrix converters can decrease the peak value of the p-n junction temperature.

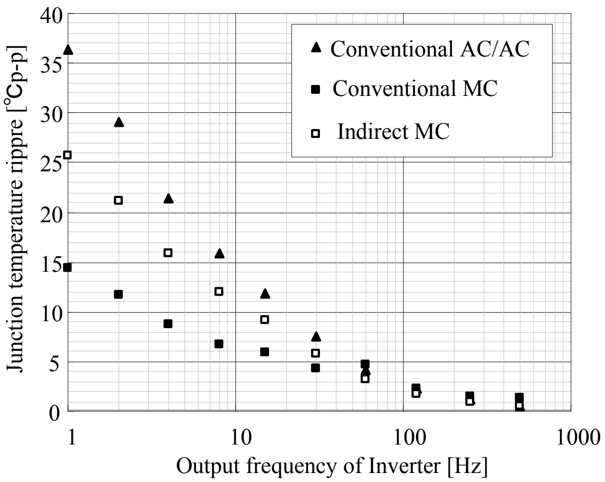


Figure 10. The relationship between the Inverter output frequency and the Junction temperature ripple.
(Output power: 7kW)

The simulation results are included to prove the validity of the matrix converter for the low speed and high torque application such as the high-power servo application.

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