Realization of High Efficiency AC link Converter System based on AC/AC Direct Conversion Techniques with RB-IGBT

Jun-ichi Itoh*, Takashi Iida*, Akihiro Odaka**

*Nagaoka University of Technology
1603-1 Kamitomioka-cho:
Niigata, 940-2188
JAPAN
itoh@vos.nagaokaut.ac.jp

**Fuji Electric Advanced Technology Co.LTD.
: 1, Fuji-machi,
Hino-city Tokyo, 191-0082
JAPAN
odaka-akihiro@fujielectric.co.jp

Abstract –

This paper proposes how to realize high efficiency of 95% for the high frequency ac link converter of three-phase input and output. The proposed control method is based on virtual converter system control method without resonant. Two novel approaches are proposed in this paper. First, reducing method of a switching loss is proposed. The proposed method realizes zero voltage switching for generator side converter without auxiliary circuit. Second, this experimental converter uses a reverse blocking IGBT (RB-IGBT) instead of a series connection diode to realize the Ac switches. The effects of the RB-IGBT is mentioned by the loss analysis using PSIM and experimental results. At last, the benefit of adopting the RB-IGBT to the ac/ac direct converter is verified through experiments.

The efficient of the proposed approach are confirmed through 1.5kW experimental system with the RB-IGBT. The clean sinusoidal waveforms for power line side current and generator side voltage, and the maximum efficiency of 94.7% are obtained. The RB-IGBT improves the efficiency of 1.9 point. The efficiency of around 95 % is very high in case of ac/ac converter with transformer system at 1kW class. In addition, the motor drive characteristics with 1.5kW induction motor are also shown in this paper.

I. INTRODUCTION

Recently, a distributed generation system is very important to protect natural resources. Power sources of a distributed generation system, for example, a wind power or a micro-gas turbine, need an interface power converter to change frequency. The interface power converter requires isolation between a generator and a power line because it is easy to protect the power line from accidents and noise. Thus, the system of the interface converter becomes a three-phase input and three-phase output with ac link converter. Moreover the interface converter also are required to be high efficiency and small size.

Those requirements are filled with an ac/ac direct converter with a high-frequency transformer. A conventional system, which consists of a PWM rectifier, a high frequency link dc/dc converter and a PWM inverter, can also convert from three-phase input to three-phase output with isolation. However this system needs a large dc link capacitor and a boost-up reactor. It is inefficient because the number of the conversion is four times in the conventional system. On the other hands, the ac/ac direct converter has no large energy storage components as an electrolytic capacitor. Besides, the reverse blocking IGBT (RB-IGBT)[11] is newly developed for ac/ac direct converter. Therefore, the low conduction loss is realized by only two times conversion and the RB-IGBT.

However, the conventional control strategies of input and output waveforms for ac/ac direct converters are very complicated. In addition, an energy management of a leakage inductance of the high-frequency transformer is difficult. The energy of the leakage inductance causes to increase snubber loss. To obtain high efficiency, some kinds of ac/ac direct converter using resonant phenomena of capacitors and reactors are proposed [1]-[9]. However the resonant converter constrains generator side voltage region, moreover resonant capacitors and reactors causes large volume.

On the other hands, the ac/ac direct converter techniques was presented by [5]. The generator side converter consists of a single-phase PWM rectifier and three-phase inverter. The proposed converter does not use a large capacitor in dc stage. However, the solution of the energy management method for the leakage inductance and the commutation method of the generator side converter are not mentioned. In addition, this method is somewhat complicated to make PWM pulses for each switch in the converter.

To obtain simple controller, a novel control strategy based on virtual converter system was propped in [10]. The proposed controller can be divided three virtual parts that consists of power line side current control part, high frequency link part and generator side voltage part, respectively. After that, PWM pulses of the ac/ac direct converter are obtained by each part of those PWM pulses. However the effect of loss suppression and the commutation method were not discussed. Moreover the conventional IGBT and diodes are used in the power line and generator side ac/ac direct converter.

This paper proposes novel method, which makes high efficiency for the three-phase input and three-phase output ac/ac direct converter with the high frequency transformer. The proposed system realizes the high efficiency without the auxiliary resonant circuit. Two novel approaches are proposed in this paper. First, the low loss and simple commutation method are proposed. The zero voltage switching and the safe commutation of the generator side converter are realized by the power line side converter control. As a result, the switching loss of the generator side can be reduced, and energy management of the generator side is realised at the same time. Second, an experimental converter uses a reverse blocking IGBT (RB-IGBT)[11][12] instead of a conventional ac switch which consist of a IGBT with series connection diode. The benefit of adopting the RB-IGBT to the ac/ac direct converter is verified through loss simulation and experiments.

The efficient of the proposed approach are confirmed through 1.5kW experiment system. The clean sinusoidal waveforms for power line side current and generator side voltage, and the maximum efficiency of 94.7% are obtained. The efficiency of around 95% is the top class value in case of three-phase ac/ac converter system with transformer at 1kW class.

II. CONTROL STRATEGY BASED ON VIRTUAL CONVERTER SYSTEM

A. Virtual indirect control

Figure 1 shows a main circuit of an ac/ac direct converter with a high-frequency ac-link. The relation between the power line side voltage t[v_r v_s v_t] and the motor(or generator) side voltage $^t[v_u\ v_v\ v_w]$ can be expressed as Equation (1).

$$\text{Power line side: } \begin{bmatrix} e_{pi} \\ e_{ni} \end{bmatrix} = \begin{bmatrix} s_{rp} & s_{sp} & s_{tp} \\ s_{rn} & s_{sn} & s_{tn} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_p \end{bmatrix}$$

$$\text{Generator side: } \begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \begin{bmatrix} s_{up} & s_{un} \\ s_{vp} & s_{vn} \\ s_{wp} & s_{wn} \end{bmatrix} \begin{bmatrix} e_{po} \\ e_{no} \end{bmatrix} \qquad (1)$$

where s_{mn} is the switching function of the switch S_{mn}. s_{mn}=1 when S_{mn} is turned-on, and s_{mn}=0 when S_{mn} is turned-off.

Figure 2 shows a main circuit of a conventional PWM rectifier and inverter system with a high-frequency ac-link converter. Same as Equation (1), the relation between the power line side voltage and the generator side voltage in figure 2 can be described as Equation (2).

$$\text{Power line side: } \begin{bmatrix} e_{pi} \\ e_{ni} \end{bmatrix} = \begin{bmatrix} s_{ap} & s_{an} \\ s_{bp} & s_{bn} \end{bmatrix} \begin{bmatrix} s_{ra} & s_{sa} & s_{ta} \\ s_{rb} & s_{sb} & s_{tb} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_p \end{bmatrix}$$

$$\text{Generator side: } \begin{bmatrix} v_r \\ v_s \\ v_p \end{bmatrix} = \begin{bmatrix} s_{uc} & s_{ud} \\ s_{vc} & s_{vd} \\ s_{wc} & s_{wd} \end{bmatrix} \begin{bmatrix} s_{cp} & s_{cn} \\ s_{dp} & s_{dn} \end{bmatrix} \begin{bmatrix} e_{po} \\ e_{no} \end{bmatrix} \quad (2)$$

In general, the operation of a converter can be described with the switching function. If the same switching function is obtained from different topology converters, then the waveforms of the power line side current and the generator side voltage in those converters become exactly the same.

Thus, from a comparison of Equations (1) and (2), it can be summarized that the power line side the ac/ac direct converter PWM pulses are obtained as

$$\begin{bmatrix} s_{rp} & s_{sp} & s_{tp} \\ s_{rn} & s_{sn} & s_{tn} \end{bmatrix} = \begin{bmatrix} s_{ap}s_{ra} + s_{an}s_{rb} & s_{ap}s_{sa} + s_{an}s_{sb} & s_{ap}s_{ta} + s_{an}s_{tb} \\ s_{bp}s_{ra} + s_{bn}s_{rb} & s_{bp}s_{sa} + s_{bn}s_{sb} & s_{bp}s_{ta} + s_{bn}s_{tb} \end{bmatrix} \qquad (3).$$

The PWM pulses of the generator side are also obtained by the same process as Equation (3). It is very easy to calculate Equation (3) by digital logic hardware to multiply and add switching functions ("1" or "0"). With this concept, all the control algorithms for the conventional PWM rectifier and inverter system can be applied to the ac/ac direct converter. The proposed control method separates the waveforms control

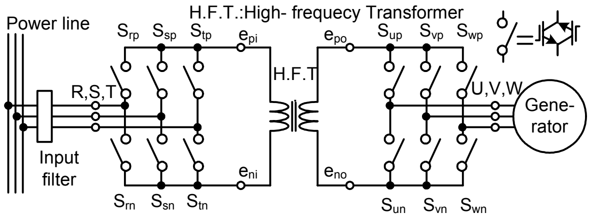


Fig. 1. Main circuit of high-frequency ac link direct converter with RB-IGBT

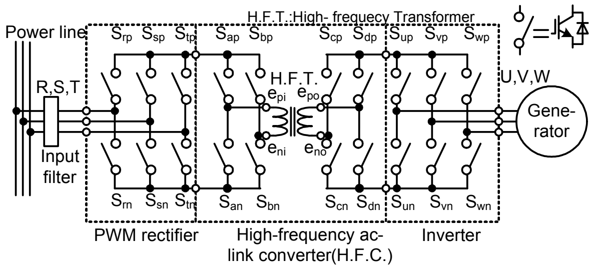


Fig. 2. Main circuit of conventional PWM rectifier and inverter system with a high-frequency ac link converter.

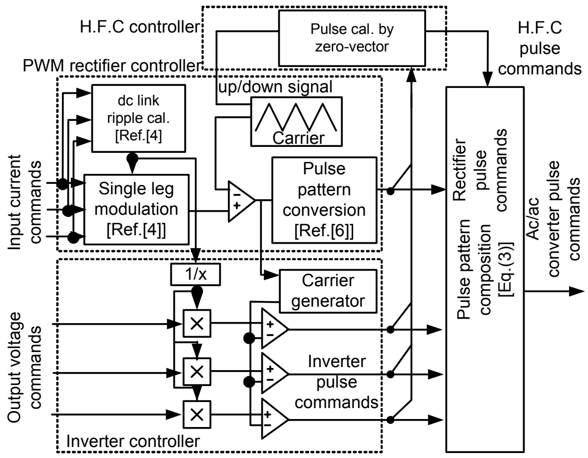


Fig. 3. Control block diagrams of proposed strategy.

of the input and output from the high-frequency link conversion. In the following discussion, it is note that the power line side converter is called the rectifier, and the generator side converter is called the inverter in figure 1.

Figure 3 shows a control block diagram of the proposed strategy. The control block consists of a virtual rectifier control, an inverter control, a high-frequency ac-link converter and a pulse pattern composition of Equation (3).

(a)Rectifier part control:

The strategy of the virtual rectifier control has two topics to realize simplicity and high-efficiency.

The first one is the adoption of the pulse pattern conversion to translate the PWM pulses of the voltage source type rectifier into the PWM pulses of the current source type. Basically, the virtual rectifier is expressed as the current source type, since the ac/ac direct converter has no boost up reactor. However, the control of the current type rectifier is complicated in general. Thus, by utilizing the pulse pattern conversion proposed in [16], the control method for the voltage source type rectifier is used, which is much simpler than the one for the current source type.

The second topic is the switching loss reduction by using a single-phase modulation. With a conventional two-phase modulation, the switching period is $2\pi/3$(electrical angle) in a half cycle of the power line side current. On the other hand, it is reduced to $\pi/3$ with the proposed single-phase modulation. Thus, the switching loss decreases by a half to the conventional method. Under the single-phase modulation, the dc-link voltage in the virtual circuit must contain the 6ω ripple to avoid the power line side current distortion.

(b)Inverter control:

The voltage command for the virtual inverter control is similar to the conventional one. It has dc-link voltage compensation as the conventional inverter control because the virtual dc-link voltage contains the 6ω ripple component as explained above. Also, there is the leakage inductance in the high-frequency transformer. Thus, to reduce the snubber loss, the two-phase modulation is used in the virtual inverter control.

Figure 4 shows the relation of the carrier signals between the virtual inverter and rectifier. There is a special carrier signal modification in the virtual inverter control. The virtual rectifier is controlled under the condition of constant dc-link current. However, the virtual dc-link current must be zero when the virtual inverter controller selects the zero voltage vectors. In the proposed method, this is achieved by controlling the slope of the inverter carrier signal as shown in figure 4. By adopting this method, the zero current period of the dc-link is distributed by the same ratio to each power line side current, as described in Equation (4).

$$\frac{T_{r0}}{T_1} = \frac{T_{s0}}{T_2} = \frac{T_{r0} + T_{s0}}{T_1 + T_2} \tag{4}$$

As a result, the average value in the switching period of the power line side currents are balanced among each phase. The slope control can be implemented simply by using a controlled up-down counter.

(c) High-frequency ac-link converter control

Basically, the pulse commands for the high-frequency link converter synchronize with the up/down signal of the PWM rectifier carrier. To reduce the switching loss, the switching pattern in this part is improved as shown in the next section.

B. Loss suppression techniques

It is the key idea that the zero voltage output period in the inverter is used to reduce the switching loss. The point of the proposed method is that the dc-link current must be zero when the virtual inverter controller is selecting zero voltage vectors.

To reduce the snubber loss by the leakage inductance of the high-frequency transformer, the power line side of the transformer is made short circuit by S_{ap},S_{bp} or S_{an},S_{bn} during the zero vector period of the inverter as shown Figure 4. The energy of the leakage inductance is discharged to the load. In addition the output of the inverter pulse keeps same switching state during the zero vector because zero voltage of the output is made by the short circuit the power line side of the transformer. Moreover, the switching of the high frequency converter of the generator side works while the inverter outputs the zero vectors. Therefore the high frequency ac link operation does not generate the switching loss. As a result, the switching loss of the inverter can be reduced because the number of the switching times during one period of the carrier in the generator side is decreased to only two times by the two-phase modulation and the zero voltage output method using the short circuit.

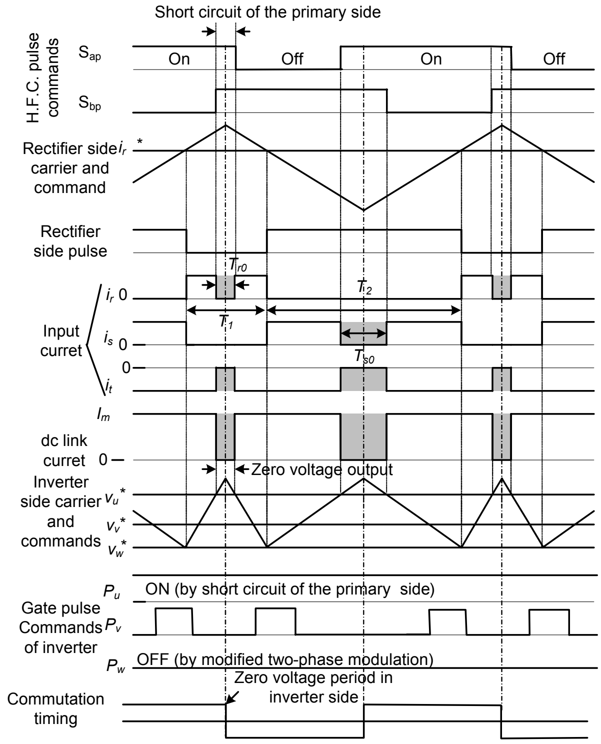


Fig. 4. Relation among rectifier and H.F.C. pulse commands, inverter carrier.

C. Commutation strategy

The commutation strategy for the generator side converter becomes very simple because the commutation is achieved during the zero voltage period of the secondary side of high-frequency transformer. The zero voltage period is made by the short circuit of the power line side converter as described in aforesaid explains. In usually ac/ac direct converter requires four-step commutation to avoid the commutation fail [15]. However the number of the commutation step is only two in this case. The over lap time to keep the current pass of the inductive load is provided during the commutation time.

The commutation strategy of the power line side converter is the same as the conventional commutation. However, the number of the switching in the power line side converter is reduced by the single-phase modulation as described in the previous section.

III. LOSS SIMULATION

We developed a simple simulation method for power semiconductor loss of the proposed ac/ac converter. This simulation method is composed by linking a circuit simulator (PSIM, Powersim Technologies Inc) and a DLL file (Dynamic

Link Library).

Figure 5 shows a configuration of the proposed loss calculation method. At first, power semiconductor characteristics for the switching loss and conduction loss are measured by a chopper test under the various current and voltage. Next, the instantaneous values of the current and the voltage at the switch timing are captured to the DLL file. In the DLL file, the power semiconductor characteristics and a loss calculation program are described. The switching loss is estimated by referring to the values of the voltage and current, which are obtained by the chopper test results. The conduction loss is estimated by the V-I characteristics from the current value. This method can estimate the power semiconductor loss regardless of the circuit configuration.

Figure 6 shows the power semiconductor characteristics of the RB-IGBT and the conventional ac switch obtained by the chopper test and V-I curve test. The forward drop voltage of the RB-IGBT becomes about half of the conventional IGBT although the switching loss is almost same.

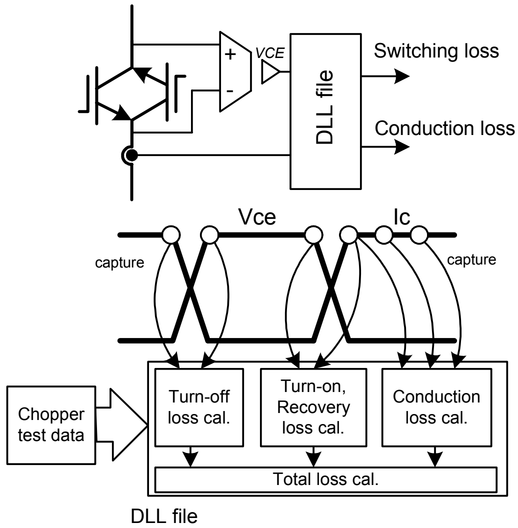
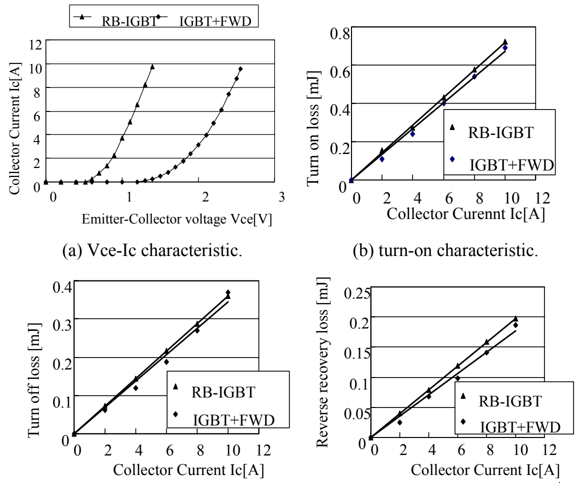


Fig. 5. Loss simulation method with DLL file



(a) Vce-Ic characteristic. (b) turn-on characteristic.

(c) turn-off characteristic. (d) recovery characteristic.

Fig. 6. Power semiconductor characteristics of the conventional IGBT and RB-IGBT

IV. EXPERIMENTAL RESULTS

A. Control performance of proposed method

Table 1 shows the condition of the experiments. Note that a commutation method based on the polarity of the input voltage [15] for the power line side converter is applied in the experiments. In addition, in order to control the output voltage, a V/f control without a voltage error compensation for the commutation is applied.

Figure 7 shows the waveforms of the power line voltage (phase voltage), the power line current and the output current in case of the R-L load instead of the generator (motor), output frequency of 40Hz. Good sinusoidal waveforms are obtained for the input and the output currents. In addition, it is noted that power factor of the input is unity. The causes of the distortion in the input and output waveforms are the voltage error depending on the current commutation.

Figure 8 shows the T.H.D. characteristics of the power line side and generator side current under 1kHz harmonic components. The T.H.D. of the power line side current of 2.6% and generator side current of 3.6% are obtained at the rating output power of 1kW, respectively. The T.H.D. of the power line side and generator side current are less than 4%, and 6% with 20% or higher load region, respectively. From those experimental results, the ac/ac direct converter can achieve a high performance by utilizing the proposed control strategy.

Table 1. Experimental conditions

Line voltage	200V	Cut off freq. of input filter	1.1kHz
Switching freq.	10kHz	Load	R-L
Input freq.	50Hz	Load P.F.	0.97

B. Effect of the Reverse blocking IGBT

Figure 9 shows the efficiency and the input power factor of the proposed converter with the RB-IGBT. It is noted that the RB-IGBT is only applied to the power line side and the conventional ac switch are used in the generator side. The input power factor is more than 99% with 30% load and higher. The maximum efficiency is 94.7% at 1.5kW output power. The efficiency of the conventional PWM rectifier and inverter system with the isolation transformer is less than around 90% at 1kW class. Therefore this suggests a clear advantage of the ac/ac direct converter with the isolation transformer in terms of efficiency, and the efficiency around 95% means on the top of the efficiency in the three-phase input three-phase output converter.

Figure 10 shows the comparison between the loss simulation results and the experimental result of the total loss. The simulation results agree well with the experimental results. It is confirmed that the loss simulation method is effective to estimate the converter loss. Next step, the loss analyses and estimation with the other construction of the ac switch are discussed by this simulation.

Figure 11 shows loss analysis at 40Hz, 1.5kW with the loss simulation and experimental results. The left side bar means

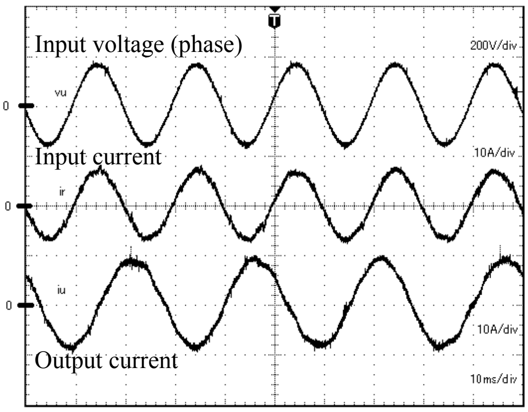


Fig. 7. Experimental results of proposed control Strategy (output frequency :40Hz).

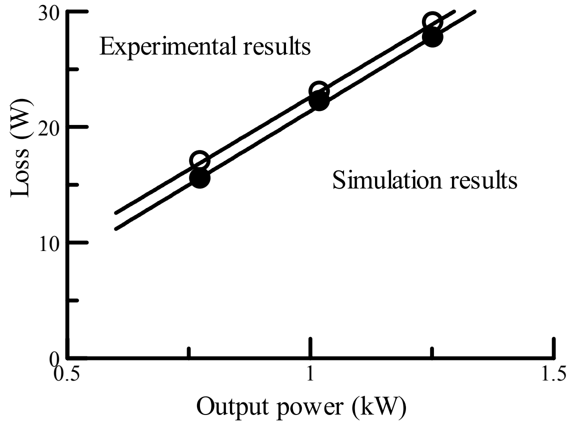


Fig. 10. Comparison of loss between simulation results and experimental results.

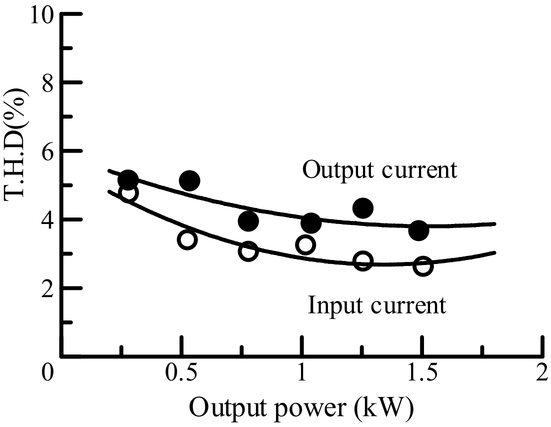


Fig. 8. T.H.D of input current and output current in the proposed converter.

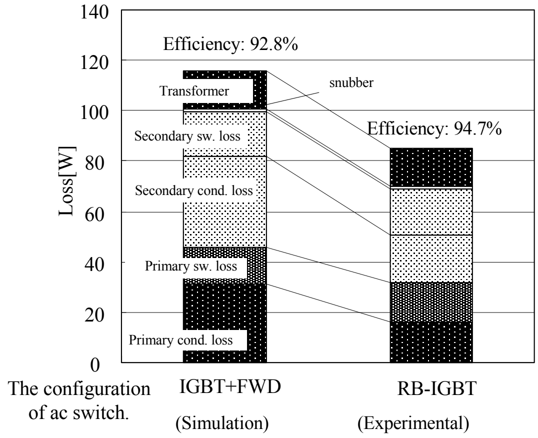


Figure 11. Comparison of the loss each ac switch at rated load.

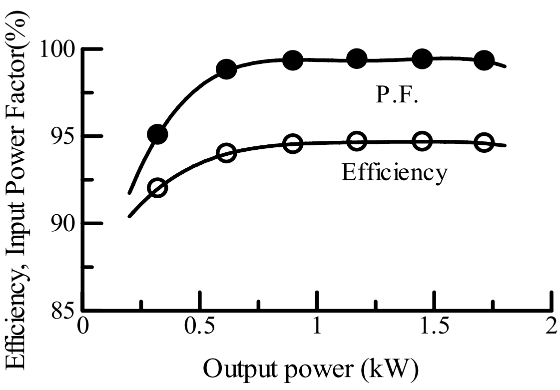


Fig. 9. Characteristics of efficiency and input power factor.

the loss simulation results with the conventional ac switch. Though the ac switches are used the conventional IGBTs and FWD, the high efficiency of 92.8% is obtained by the proposed control method. Moreover, the total efficiency of 94.7% is obtained by changing the all the conventional ac switch to the RB-IGBT. The conduction loss decreases to about 2/3 of the conventional ac switch. The RB-IGBT can improve the efficiency of 1.9points against the conventional ac switch. The loss of the transformer accounts for about 20% of the total loss. To improve the efficiency, the design to of the high-frequency transformer is important.

Figure 12 shows power line voltage (phase voltage) , power line current and motor current waveforms in case of the general purpose induction motor instead of the R-L load. The ratings of the motor are power: 1.5kW, voltage: 200V, frequency: 50Hz, speed: 1420r/min. The motoring and generating operation is confirmed in Figure 12(a) and (b), respectively. In the both case, the power line current is almost kept sinusoidal waveform and unity power factor. In addition the motor current is also keeping sinusoidal waveform. It is noted that the distortion of the power line side and generator side current are occurred by the commutation error. Thus, the compensation of the commutation error for the proposed circuit or the current control using feedback control is needed to improve the current waveforms.

V.CONCLUSIONS

. In this paper, two approaches to make the high efficiency isolated ac/ac conversion system are proposed. The loss is suppressed by the following techniques without the restriction of the PWM pattern as resonant type converter.

- The number of the switching times in the generator side is reduced by the two-phase modulation and the short circuit of the power line side in transformer. The proposed control method is realized by the virtual converter system control method which can be separated into the rectifier, dc/dc high-frequency link and inverter stage despite the ac/ac direct converter.

- The commutation of the generator side converter becomes simple. The number of the proposed commutation timing is only two because the commutation is achieved during zero voltage timing of the generator side converter.
- The effect of the RB-IGBT is confirmed by the loss simulation and experimental results. As a results, the high efficiency of 94.7% is obtained at 1.5kW load in the experimental results, and it is improved about 1.9 point against a conventional device.

In future works, the input and output waveforms will be improved by the voltage error compensation, and the details of the motor drive characteristics will be mentioned.

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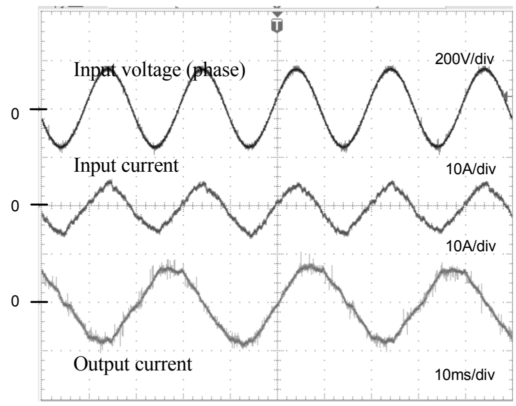
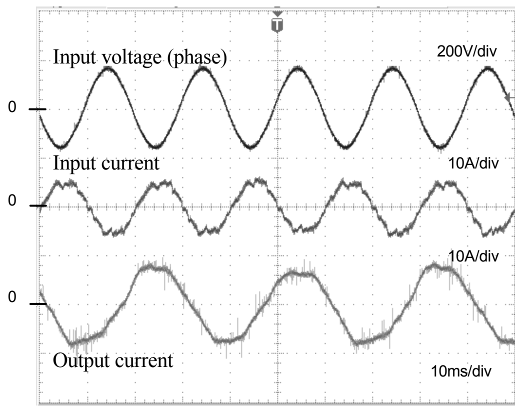


(a)Motoring



(b)Generating

Fig. 12 Input and output current waveforms in case of the induction motor under ratting torque.

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