

Ripple Current Reduction of a Fuel Cell for a Single-Phase Isolated Converter using a DC Active Filter with a Center Tap

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Abstract- This paper proposes a ripple reduction method in current without using any additional switching devices. The current ripple that has double frequency component of the power supply is generated in the DC part when a single-phase PWM inverter is used for a grid connection. The current ripple causes short lifetime for electrolytic capacitors, batteries and fuel cells. The proposed circuit realizes a DC active filter function without increasing the number of the switching device because the energy buffer capacitor is connected to the center tap of the isolation transformer. In addition, the buffer capacitor voltage is controlled by the common mode voltage of the inverter. This paper describes the features of the proposed circuit, control strategy and experimental results. As a result, about 1/5 times of the ripple can be reduced.

I. INTRODUCTION

Recently, green energy sources such as wind power systems, photovoltaic cells and fuel cells, have been extensively studied in response to the global warming and environmental issues. The fuel cell is an important technology for mobile applications and power grid distribution system since it does not draining CO₂.

A fuel cell system requires a grid interconnection converter to supply power to the power grid. A grid interconnection converter using an isolation transformer is preferred for power grid distribution system in terms of surge protection and noise reduction. Moreover, size reduction and high efficiency are also required essentially [1-6].

However, one problem with the fuel cell system is the short lifetime, which is dependent on the ripple current. Therefore, in order to extend the lifetime, the fuel cell ripple current must be reduced in the grid interconnection converter [7]. However, when single-phase PWM inverter is used for grid connection system, the grid frequency happens to have double frequency of the power ripple. This current ripple prevents long lifetime of the fuel cell. Therefore, in conventional grid connection inverters, large electrolytic capacitors are connected in parallel to the fuel cell in order to reduce the ripple. However, the large-sized electrolysis capacitor causes big volume and expensive device cost.

To reduce the current ripple, some methods without using a large-sized electrolytic capacitor have been proposed. For example, an active filter is applied in DC link part [8-10]. The DC active filter consists of a small capacitor as energy buffer,

a reactor to reduce the switching ripple and DC chopper. The DC chopper injects the ripple current to avoid power ripple. Capacitance can be lower since the terminal voltage of the capacitor can be widely changed. However, the numbers of the switching devices increased results the DC chopper is high cost and large volume. Likewise, other configurations of the DC active filter have the similar problems.

This paper proposes a new circuit topology including a DC active filter function without extra switching devices. The proposed circuit consists of the isolated DC/DC converter and interconnection inverter, and achieved the DC active filter function by using the center tap of the isolation transformer. Besides, one feature of the proposed converter is that the primary side inverter in the DC/DC converter is controlled by the common mode voltage and differential voltage, individually. The ripple current is suppressed by the common mode voltage control of the DC/DC converter and the main power flow is controlled by the differential mode voltage.

At first, this paper introduces the conventional and proposed circuit topologies with the principle of the current ripple suppression. Second, the control method of the proposed circuit is described. In addition, this paper indicates the design of the energy buffer capacitor and transformer which the maximum power ripple can be accepted. Furthermore, experimental results are shown in order to confirm the validity of the proposed circuit.

II. PROPOSED CIRCUIT CONFIGURATIONS

Figure 1 shows a conventional circuit that consists of the first stage inverter for the medium frequency link, an transformer, a diode rectifier, and a grid interconnection inverter. When the interconnection current and power grid voltage are sinusoidal waveforms, the instantiations power p of the grid interconnection is obtained by (1) at unity power factor

$$\begin{aligned} p &= \sqrt{2}I \sin(\omega t) \cdot \sqrt{2}V \sin(\omega t) \\ &= VI \{1 - \cos(2\omega t)\} \end{aligned} \quad (1)$$

where I and V are the RMS value of the interconnection current and the grid voltage, and ω is the grid angular frequency.

Thus, the instantaneous power has a ripple that is double frequency of the power grid frequency. To reduce the ripple power of the DC power source, such as a fuel cell, battery or photovoltaic cell, large electric capacitors, C_{DC1} and C_{DC2} , are used in the converter, as shown in Figure 1. The use of large electrolytic capacitors precludes reduction in size and cost.

Figure 2 shows the other conventional circuit using a DC active filter, which is constructed with a DC chopper and an energy buffer capacitor C_f . The capacitor C_f is used as an energy buffer to absorb the ripple power. The inductor L_f can suppress the switching current. The voltage of the capacitor C_f is controlled at the double frequency of the power grid frequency. As a result, the ripple power does not appear in V_{dc} , despite the use of small capacitors C_{DC1} and C_{DC2} . However, the problem of this method is that the number of the switching elements had to increase.

Figure 3 shows the proposed circuit that combines the first stage inverter and DC active filter function. The energy buffer capacitor C_f is connected to the center tap of the medium frequency transformer. The zero vector of the full bridge first stage inverter is used to control the center tap potential voltage. In addition, the leakage inductance of the transformer is used to suppress the switching current instead of L_f .

Table 1 shows comparison of the number of the switching device and capacitor capacity among the conventional circuit, the conventional circuit with the DC active filter and the proposed circuit. The proposed circuit does not require an additional switching device and an inductor, in comparison with the conventional circuit with the DC active filter. Note that the current rating of the power device in the first stage inverter and transformer are slightly larger than that of the conventional circuit because the DC active filter current flows in the first stage inverter and the transformer.

III. CONTROL METHOD

The first stage inverter in this proposed circuit has two roles which are performed as a DC/DC converter and a DC active filter. These roles are achieved by controlling the common and differential mode voltage in the first stage inverter. This chapter explains the principle of the proposed control method and the design method for the buffer capacitor and the transformer.

A. Switching pattern generation method

Figure 4 illustrates the two switching modes of the first stage inverter in the proposed circuit. In the differential mode, the terminal voltage of the transformer is controlled as shown in Figs. 4(a) and (b), and in the common mode, the center tap voltage is controlled as shown in Figs. 4(c) and (d). In other words, the inverter outputs the zero voltage vectors (00 and 11 are two) in common mode operation. When the zero voltage vectors are selected, the line to line voltage of transformer is zero. However, the center tap voltage is either V_{dc} or zero, depending on the zero vector of Figs. 4(c) or (d), respectively. Thus, by controlling the ratio of the zero vectors, the center tap voltage can be controlled. It should be noted that the

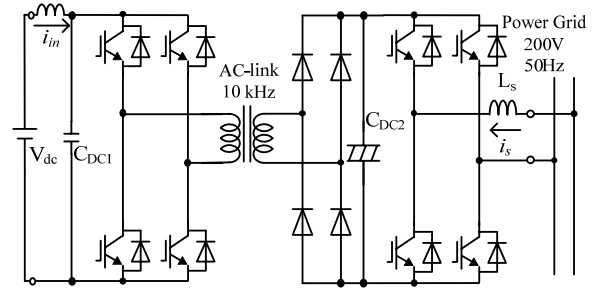


Fig. 1. Conventional circuit.

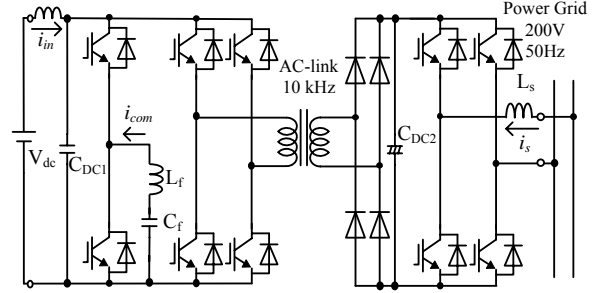


Fig. 2. Conventional circuit with DC active filter.

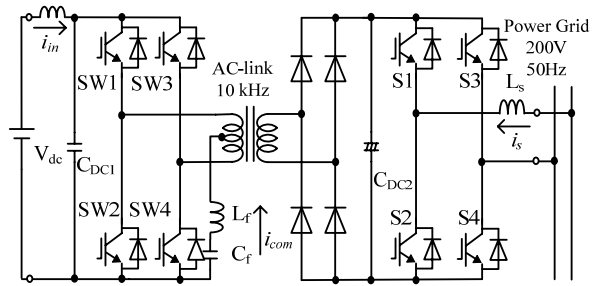


Fig. 3. Proposed circuit.

Table1. Comparison device number and capacitance of capacitor.

	Device Number	DC Link Capacitor
Conventional Circuit	8	large
Conventional circuit With DC active filter	10	small
Proposed Circuit	8	small

output switching pattern must included the zero vector period. Therefore, the voltage transfer ratio of the first stage inverter is limited by the DC active filter control. As a result, the terminal voltage of the transformer is decreased.

Figure 5 shows the control block diagram of the proposed circuit. To suppress the ripple current of the fuel cell, all the ripples current are provided by the energy buffer capacitor. Therefore, the capacitor current command i_{com}^* is obtained by calculating the power ripple. The grid interconnection control can be applied to the conventional control method, which uses an automatic current regulator (ACR) for the interconnection current command.

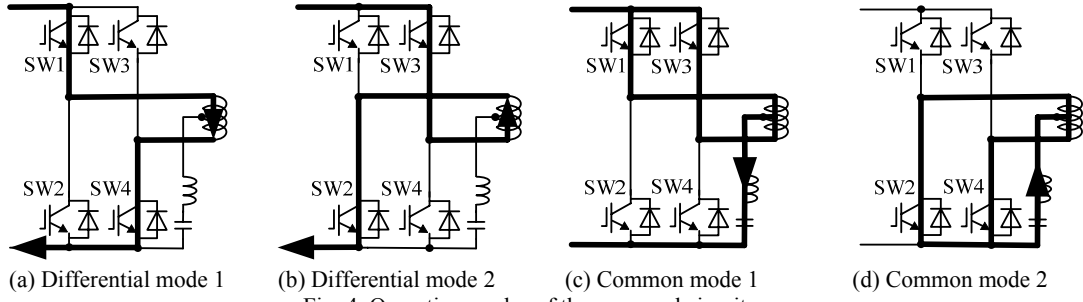


Fig. 4. Operation modes of the proposed circuit.

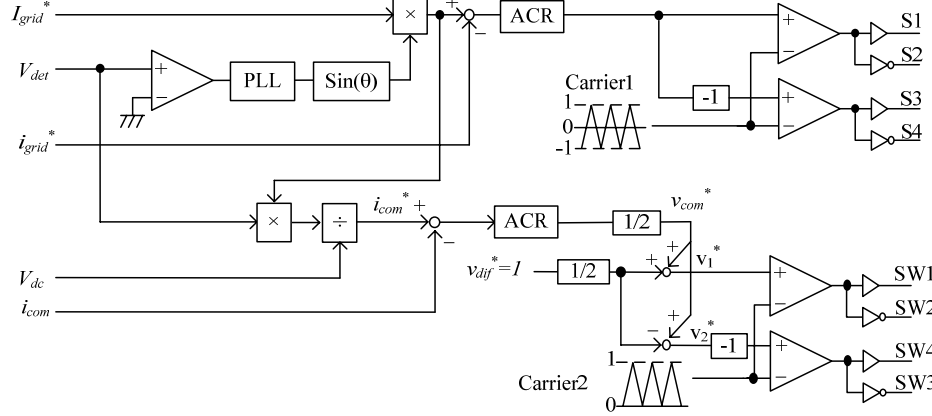


Fig. 5. Control block diagrams.

The DC active filter voltage command v_{com}^* is obtained by the PI regulator in the current regulator. The differential mode voltage command v_{dif}^* is set to 1 as the maximum value, in order to obtain the maximum terminal voltage of the transformer.

The feature of the proposed circuit control is that the DC active filter voltage command v_{com}^* is added to the differential voltage command v_{dif}^* as the common mode voltage. The output voltage commands v_1^* and v_2^* for each leg in the first stage inverter are obtained by (2).

$$\begin{cases} v_1^* = \frac{1}{2}(v_{com}^* + v_{dif}^*) \\ v_2^* = \frac{1}{2}(v_{com}^* - v_{dif}^*) \end{cases} \quad (2)$$

B. Design of the buffer capacitor for the DC active filter operation

The buffer capacitor is used as an energy storage element of the active filter. The capacitor C_f has to absorb the power ripple for half cycle of the power grid. Thus, the required storage energy W_C is given by (3) from (1) and the capacitor energy W_f is obtained by (4)

$$W_C = \int_0^{T/4} P_{in} \cos 2\omega t dt = \frac{P_{in}}{\omega} \quad (3)$$

$$W_f = \frac{1}{2} C_f (V_{fmax}^2 - V_{fmin}^2) \quad (4)$$

where P_{in} is the input power, ω is angle frequency of the power grid, V_{fmax} and V_{fmin} are the maximum and minimum voltage of C_f , respectively.

Therefore, the required capacitance C_f is given by (5) from (3) and (4).

$$C_f = \frac{2P_{in}}{\omega((V_{cf0} + \Delta V_{cf}/2)^2 - (V_{cf0} - \Delta V_{cf}/2)^2)} = \frac{P_{in}}{\omega V_{cf0} \Delta V_{cf}} \quad (5)$$

where V_{cf0} and ΔV_{cf} are the average voltage and the variation voltage of C_f , respectively.

Figure 6 shows the relation between the capacitance and the voltage variation ΔV_{cf} of the capacitor to compensate the power ripple at 1 kW and V_{cf0} of 150 V, according to (5). The capacitance can be reduced greatly by the capacitor voltage variation.

It is noted that reactor L_f is set to decrease the switching ripple. That is, the reactor L_f depends on the switching frequency of the first stage inverter. The leakage inductance of the transformer is used as L_f .

C. Design of the transformer.

The major focus in the design for the transformer is the current capacity. This is because the transformer has two functions; first is to be a DC active filter and second is to be an isolation transformer. The transformer current, I_{trans} , is equaled to the sum of the active filter current I_{com} and the current I_{dif} which is according to the output power is shown in (6).

$$I_{trans} = I_{dif} + \frac{I_{com}}{2} \quad (6)$$

Note that in (6) the active filter current is divided by 2 because the transformer winding is connected in parallel to the

center tap in the common mode circuit as shown in Figs.4 (c) and (d).

The common mode voltage controls the capacitor voltage variation and for the differential mode voltage, it controls the transmission power to the power grid. The common mode voltage should be changed widely from the viewpoint of capacitance suppression as shown in (5). However, the period of the differential mode becomes short when the common mode voltage is widely changed.

Figure 7 shows the differential mode current waveforms and the terminal voltage waveforms of the transformer in the case of common mode command is 0 and 0.3 p.u respectively, given at the same output power. The differential mode current increases when the common mode voltage increases, because the power transmission period is shaved off by the common mode voltage. Therefore, the duty ratio D_{diff} for the differential mode can be constrained by (7).

$$D_{diff} + D_{com} = 1 \quad (7)$$

where D_{com} is the duty ratio for the common mode voltage.

The duty ratio for the common mode voltage is obtained by (8) because the average voltage V_{cf0} of C_f is half of the DC voltage.

$$D_{com} = \frac{\Delta V_{cf}}{2V_{cf0}} = \frac{\Delta V_{cf}}{V_{dc}} \quad (8)$$

where V_{dc} is the DC voltage of the first stage inverter.

Also, the differential mode current I_{dif} is obtained by (10) using (7) and (8).

$$I_{dif} = \frac{P_{in}}{V_{dc} D_{diff_max}} = \frac{P_{in}}{V_{dc} - \Delta V_{cf}} \quad (9)$$

On the other hands, the common mode current I_{com} is shown in (10) because the maximum value of the power ripple is the double of the input power.

$$I_{com} = \frac{2P_{in}}{V_{dc}} \quad (10)$$

Finally, the transformer current I_{trans} is obtained by (11) from (6), (9), and (10).

$$I_{trans} = I_{dif} + \frac{I_{com}}{2} = \frac{P_{in}}{V_{dc} - \Delta V_{cf}} + \frac{P_{in}}{V_{dc}} \quad (11)$$

It is noted that I_{com} in (10) is the peak value of the common mode current. Therefore, RMS value $I_{trans(rms)}$ of the transformer current, which is used to decide the thickness of transformer winding, is obtained by (12).

$$I_{trans(RMS)} = I_{dif} + \frac{I_{com}}{2} = \frac{P_{in}}{V_{dc} - \Delta V_{cf}} + \frac{P_{in}}{\sqrt{2}V_{dc}} \quad (12)$$

Figure 8 presents the relation between the transformer current and the capacitor voltage variation at $V_{cf0} = 150$ V, $P_{in} = 1$ kW and $V_{dc} = 300$ V. As the capacitor voltage variation becomes large, a smaller active filter capacitor C_f can be achieved. However, as the larger the capacitor voltage variation becomes, it results the system required a large current capacity transformer.

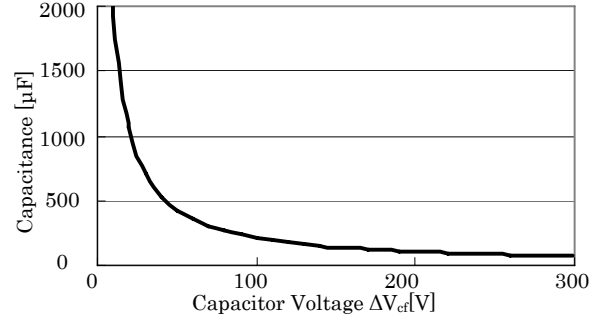


Fig. 6. Required capacitance for power ripple compensation. ($P_{in}:1$ kW, $V_{dc}:300$ V, $V_{cf0}:150$ V)

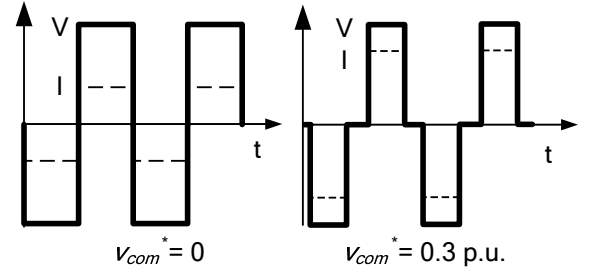


Fig. 7. The current and voltage wave pattern by the difference of the common mode duty ratio at the constant power.

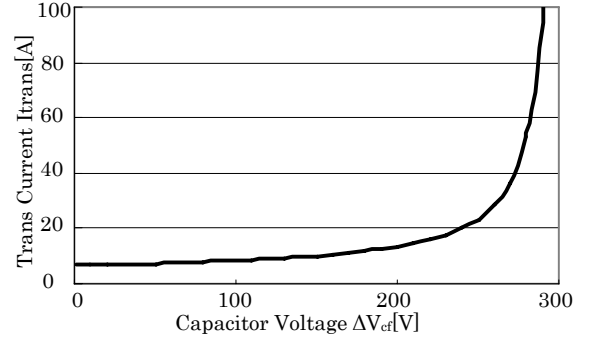


Fig. 8. The current capacity of the transformer which is necessary for compensation ($P_{in}:1$ kW, $V_{dc}:300$ V, $V_{cf0}:150$ V)

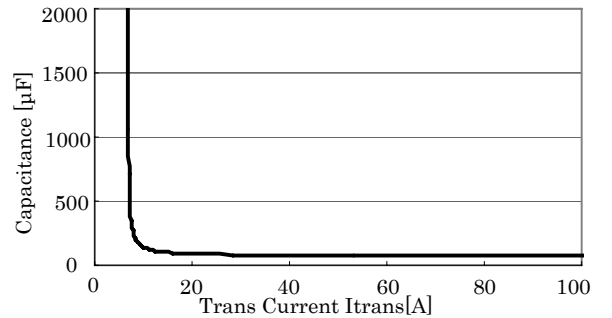


Fig. 9. The transformer current capacity and capacitance which is necessary for compensation. ($P_{in}:1$ kW, $V_{dc}:300$ V, $V_{cf0}:150$ V)

In addition, the relation between the transformer current and the capacitance is represented by (13) from (5), and (11).

$$C_f = \frac{P_{in}(P_{in} - V_{dc} I_{trans})}{\omega V_{cf0} V_{dc} (2P_{in} - V_{dc} I_{trans})} \quad (13)$$

Figure 9 will further explain the relation between the transformer current and the capacitance $V_{c\phi} = 150$ V, $P_{in} = 1$ kW and $V_{dc} = 300$ V. As can see from Fig. 9, a choice of picking up a smaller capacitance results a larger current capacity transformer is chosen. For example, for a 1 kW system, if a 150 μ F capacitor is chosen, then the transformer which has current capacity of more than 10A needs to be considered. In other words, the proposed method requires a fat winding transformer in comparison with that of the conventional circuit.

Note that the number of turns in a winding for the transformer is calculated from (14) as same as the conventional transformer.

$$N = \frac{V_{dc}}{4fSB} \quad (14)$$

where, N is the number of turns in a winding, f is the switching frequency of the first stage inverter, B is the flux density of the core, S is the section area of the core.

IV. EXPERIMENTAL RESULTS

The proposed converter was tested under experimental conditions which are shown in Table 2 to confirm the validity of the proposed circuit operation. The auxiliary inductor is connected to the center tap of the transformer, because the leakage inductance of the transformer is not sufficient to reduce the switching ripple current.

Figure 10 shows the operation waveforms of the conventional circuit without the DC active filter. The sinusoidal grid current waveform and unity power factor are obtained; however, the DC input current has a large ripple current component of 100 Hz.

Figure 11 shows the operation waveforms of the proposed converter. The ripple of the DC input current is suppressed to 20% of that with the conventional circuit, indicating that the DC active filter function is effective.

Figure 12 shows the operation waveforms of the conventional circuit using a large electrolytic capacitor of 2200 μ F. This circuit was tested in order to determine the reduction in the DC ripple current by using a large electrolytic capacitor. Although a large electrolytic capacitor, which is 20 times that shown in Figure 11, is used, the DC input current did not reduce significantly.

Figure 13 shows the DC input current total harmonic distortion (THD) of the conventional and proposed circuit, which is defined by (14).

$$I_{DC_THD} = \frac{\sqrt{\sum I_n^2}}{I_{DC}} \quad (15)$$

where I_n is harmonic components and I_{dc} is DC component.

The major harmonic component in the input current is 100 Hz. In a conventional circuit, the DC input current THD increases accordingly to the increment of the output power. In contrast, the DC input current THD decreases despite the increment of the output power in the proposed circuit. That is,

Table 2. Experimental parameters.

Output power	1 kW
Grid frequency	50 Hz
Grid voltage	200 V
AC Link frequency	10 kHz
Active filter inductor	5 mH
Energy buffer capacitor	440 μ F
DC link capacitor (Proposed circuit)	110 μ F
DC link capacitor (Conventional circuit)	2200 μ F

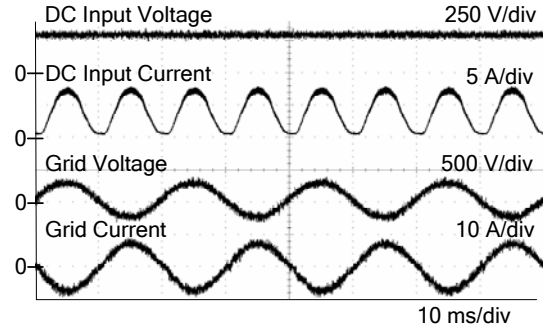


Fig.10. Operation waveforms of the conventional circuit without a DC active filter.

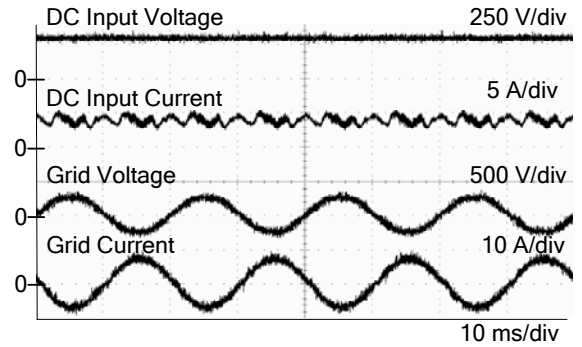


Fig.11. Operation waveforms of the proposed circuit.

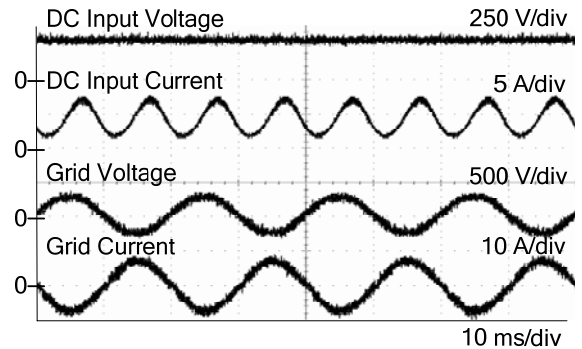


Fig.12. Operation waveforms of the conventional circuit with a large electrolytic capacitor $C_{DC2}=2200$ μ F.

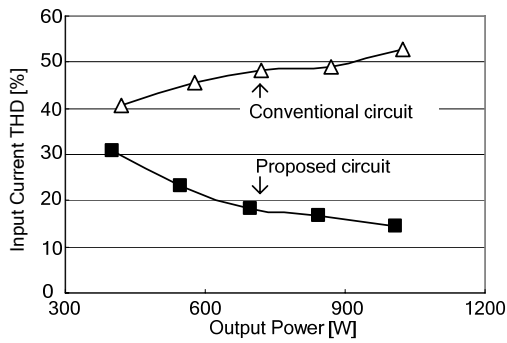


Fig.13. Input DC Current distortion factor

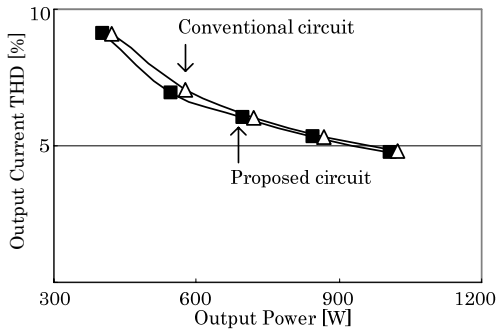


Fig.14. THD of Grid connection Current.

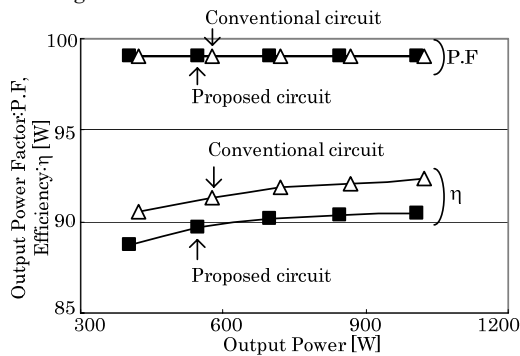


Fig.15. Efficiency and Grid connection power factor.

the proposed circuit is suitable for the high power application due to effective in high output power region.

Figure 14 shows the THD of the grid interconnection current of the conventional and proposed circuit. Almost the same current THD values were obtained. The proposed circuit can achieve the same performance level as the conventional does.

Figure 15 shows the efficiency and the grid interconnection power factor of the conventional and proposed circuit. The efficiency of the conventional circuit is higher than the proposed circuit. One of the reasons power loss had increased is because of the increasing current in the transformer. Therefore, the efficiency of the proposed circuit can be improved if the design of the transformer has been optimized. Note that the proposed converter has good performance as the grid interconnection converter because both power factors of the proposed circuit and the conventional circuit were 99%.

Therefore, these experimental results confirmed that the proposed converter is valid for the reduction of the DC input ripple current in the DC power supply, without the need of large electrolytic capacitors.

V. CONCLUSIONS

A novel single-phase isolated converter was proposed for grid interconnection application. The ripple current in a DC power supply, such as a fuel cell, battery or photovoltaic cell, can be reduced by a proper operation of the DC active filter. The main feature of the proposed circuit is that it does not require additional switching devices, because the zero vector of the first stage inverter is controlled as the DC active filter. A 1kW prototype was constructed based on the proposed circuit and the experimental results were obtained as follow,

- 1) The ripple current can be decreased to 20% lower than a conventional circuit.
- 2) The proposed circuit shows a degree of effectiveness in a high power application.
- 3) The requirement of the total electrolytic capacitor in the system decreases to 1/4 times.
- 4) The DC active filter operation in the proposed method circuit does not interference the grid interconnection current control.

In future, the optimization of the transformer and constructing a high power prototype will be carried out.

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