A 1kW Grid-Connected Converter System for PEFC

Ryuji Yamada, Nobuyuki Kobayashi, Kazuaki Mino
Fuji Electric Advanced Technology Co., Ltd., 1, Fuji-machi, Hino-city, Tokyo, Japan

***Abstract*-- We have developed a small-size high-efficiency grid-connected converter system for a 1kW PEFC (Polymer Electrolyte Fuel Cell) unit, which consists of a novel isolated dc-dc converter and a single-phase inverter whose output voltage is 200V. In order to reduce reverse recovery losses of diodes in the secondary circuit of the dc-dc converter, two rectifiers with 600V diodes and an inductor connected in series are employed instead of one rectifier with higher voltage diodes that have a slow reverse recovery characteristic. Furthermore, we have applied a new low-loss clamp-type snubber to the diodes. The efficiency of the converter system is 91.1%, and the efficiency of the dc-dc converter in the system is 94.6% at the nominal condition.**

***Index Terms*-- dc-dc converter, grid, PEFC, snubber**

I. INTRODUCTION

An output of a PEFC (Polymer Electrolyte Fuel Cell) is low dc voltage. To utilize a PEFC output in a grid, a step-up and a dc-ac conversion are necessary. Due to characteristics of PEFCs, necessary functions for converters are as follows:

(1) An isolation between an input and an output of the system (for protection of the PEFC unit and grid);

(2) A compensation of FC (fuel cell) unit output voltage variations (depending on output power and year-to-year change).

From user side, the followings are required for converters:

(3) A high conversion efficiency (for reduction of running cost);

(4) Minimization of the size (because PEFC is used in general households, the installation area must be small).

To realize (1) and (4), use of a transformer operating with the commercial frequency is inappropriate. Accordingly, it is necessary to use a dc-dc converter that has a high frequency isolated transformer, and an inverter is needed to connect to a grid. Furthermore, the system has to consume a lower loss from (3). One of the candidates for the dc-dc converter is a resonant type [1]. Recently, high-speed MOSFETs using a supper junction technology have been developed, which brings a low switching loss even with a hard switching if the switching frequency is not high, e.g. less than 100kHz. Therefore, we selected a PWM-controlled dc-dc converter with hard switching for a grid-connected converter system in order to simplify the circuit configuration and the operation compared to a resonant type dc-dc converter. In the system, an inductor such as shown in Fig.1 is used for smoothing the rectified currents. The technical issues of those circuit configurations are as follows.

A turns ratio of the transformer must be set so that a required output voltage is obtained at minimum input voltage. Maximum peak voltage of the rectified voltage v_{rec} generates at maximum input voltage. In the case where input voltage range is large, maximum peak value of v_{rec} is therefore high and the voltage across the diodes is also high.

Moreover, since the rectifiers are not clamped at a constant voltage, it is difficult to reduce a loss in snubber [2]. In case where a conventional RCD snubber circuit as depicted in Fig.1 (a) is employed, an unnecessary current flows into the snubber resistor because a peak value of v_{rec} is higher than V_o, which results in a higher loss in the snubber resistor. In addition, an RC snubber illustrated in Fig.1 (b) is not suitable for high output voltage applications and high switching frequency operation such as this system. A loss in RC snubber P_s is approximately shown as

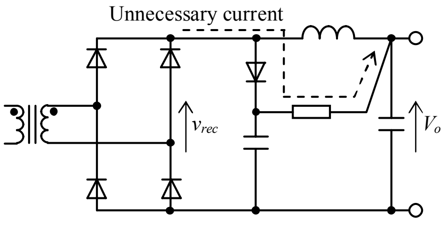
$$P_s = C\hat{v}_{rec}{}^2 \times f \tag{1}$$

where C is a capacitance of the snubber, $\hat{v}_{rec}$ is a peak value of v_{rec}(similar in bellow), and f is an operating frequency (double of frequency in the primary circuit) of the rectifier. In the system, $\hat{v}_{rec}$ is higher compared with general switching power supply applications outputting 5V or 48V and loss in the snubber depends on square of $\hat{v}_{rec}$. Consequently, the RCD and RC snubbers are not suitable in the system due to a high loss.

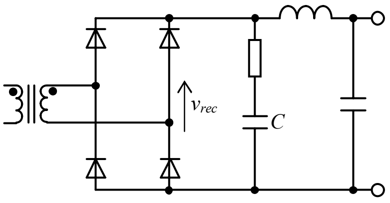
In this paper, we have proposed a new rectifier circuit to reduce voltage rating of diodes and loss in snubber.

II. SPECIFICATIONS

The specifications of the grid-connected converter system applied to a 1kW PEFC are shown in Table I. The output voltage of the PEFC unit at the maximum power is 67.4V (without consideration of year-to-year change). However, the PEFC has the characteristic such that the output voltage is higher at around zero output current. Therefore, the converter must be able to operate at the maximum input voltage 92V at zero current, which occurs at the start-up and the shut-down of the system.



(a) RCD snubber



(b) RC snubber

Fig.1. Configurations of conventional snubber circuits applied to the secondary circuit of dc-dc converters

TABLE I. SPECIFICATIONS

Item		Specification
Input	Maximum power	1280W
	FC unit voltage at the maximum power	67.4V
	Voltage variation	50-92V
	FC unit current at the maximum power	19A
	Current variation	0-20A
Converter	dc-link voltage	340-365V
	Switching frequency of dc-dc converter	60kHz
	Switching frequency of inverter	15kHz
Output	Nominal grid voltage	200V (1-phase 2-wire)
	Voltage variation	170-220V
	Nominal current	5.8A
	Frequency	50/60Hz
Size		219mm×326mm×88mm (except the air duct)

III. PROPOSED DC-DC CONVERTER

Fig.2 shows the circuit configuration of the proposed dc-dc converter including the snubbers and Fig.3 shows the theoretical time behaviors of the operation. The low voltage MOSFETs are utilized with a high switching frequency. All MOSFETs are turned-off in the zero voltage periods, which causes lower conduction losses if compared to phase-shift controlled dc-dc converters. In order to reduce reverse recovery losses of diodes in the secondary circuit, two rectifiers employing 600V diodes are connected in series instead of using one rectifier with high voltage diodes having slow recovery characteristics. Table II shows a comparison of the candidates of diodes in the rectifier. Since the diodes whose voltage ratings are more than 800V have a longer reverse recovery time, it is therefore difficult to employ them to a rectifier operating with a high switching frequency such as 60kHz in this system.

By connecting D_5 and D_6 to the diode bridges in parallel, conduction losses can be reduced because the secondary current during circulating periods is bypassed. C_2 and C_3 are used for a protection of the transformers from a magnetic saturation.

In addition, it is possible to apply the clamp-type snubber by connecting the inductor L_1 between the diode bridges. The snubbers can be employed by connecting the discharge resisters R_{S1} and R_{S2} to the points N and P, respectively. At least 340V is necessary for E_d to output the maximum sinusoidal voltage of 220V, which is taken into account the voltage drops and the maximum modulation ratio of the inverter. The turns ratio of the transformers is designed to be 1:3.83 so that the system can output the required maximum voltage 220V at the minimum FC unit voltage 50V. The peak voltage on one of the secondary windings of the transformers is 352V at the maximum input voltage 92V. Then $\hat{v}_{rec1}$ and $\hat{v}_{rec2}$ are also 352V (The voltage drops are neglected here). On the other hand, E_d is controlled at 365V, which is slightly higher than $\hat{v}_{rec1}$ and $\hat{v}_{rec2}$. The voltages of the snubber capacitors C_{S1} and C_{S2} are clamped at E_d. Therefore, an unnecessary discharge from C_{S1} and C_{S2} to C_4 does not occur. This results in a reduction of charge and discharge losses.

The dc-dc converter cannot output E_d at 365V when the input voltage is low. In such case the converter proportionally reduces E_d until 340V depending on the input voltage variation. Even in this case, $\hat{v}_{rec1}$ and $\hat{v}_{rec2}$ are always smaller than E_d because $\hat{v}_{rec1}$ and $\hat{v}_{rec2}$ are also reduced with the input voltage. Therefore, an unnecessary discharge current to C_4 does not flow under any operating conditions.

TABLE II
COMPARISON OF FAST RECOVERY DIODES MANUFACTURED BY FUJI ELECTRIC DEVICE TECHNOLOGY

Product number	ESAD39M-06D	YG912S6	YG225D8	ERD08M-15
Voltage rating	600V	600V	800V	1500V
Maximum average current (Square wave, duty=1/2)	10A(T_c=85deg C)	10A(T_c=92deg C)	10A(T_c=95deg C)	5A(T_c=115deg C)
Forward voltage drop	2.5V max (I_F=4A)	1.7Vmax (I_F=10A)	1.5V max (I_F=2.5A)	1.2Vmax (I_F=5A)
Reverse recovery time (I_F=0.1A,I_R=0.2A,Irec=0.05A)	50ns	50ns	400ns	1500ns

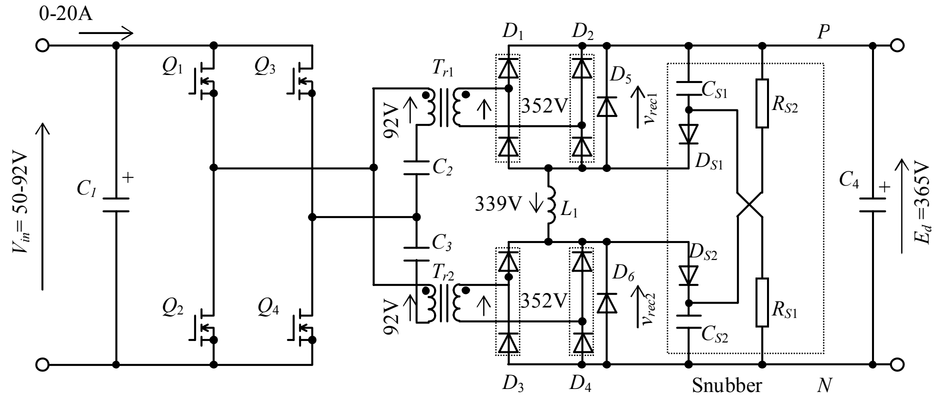
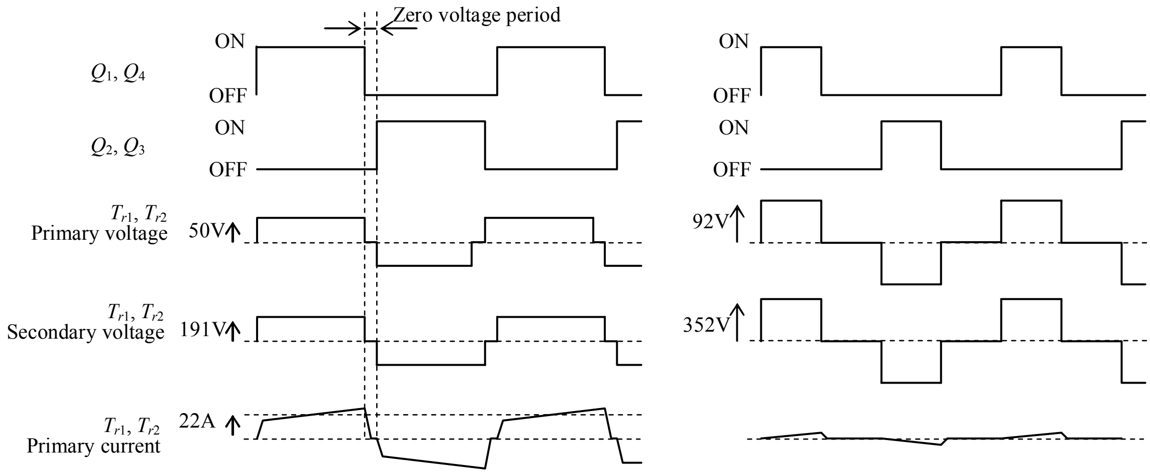


Fig.2. Circuit configuration of proposed dc-dc converter



(a) Input voltage=50V

(b) Input voltage=92V

Fig.3. Principle of operation of the proposed dc-dc converter

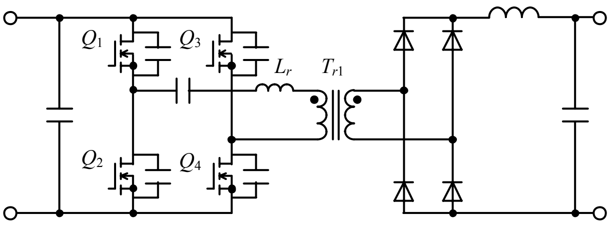


Fig.4. Circuit configuration of conventional phase-shift dc-dc converter

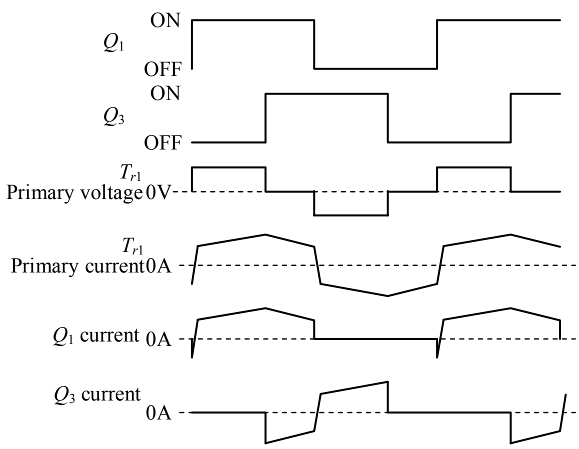


Fig.5. Principle of operation of the conventional phase-shift dc-dc converter

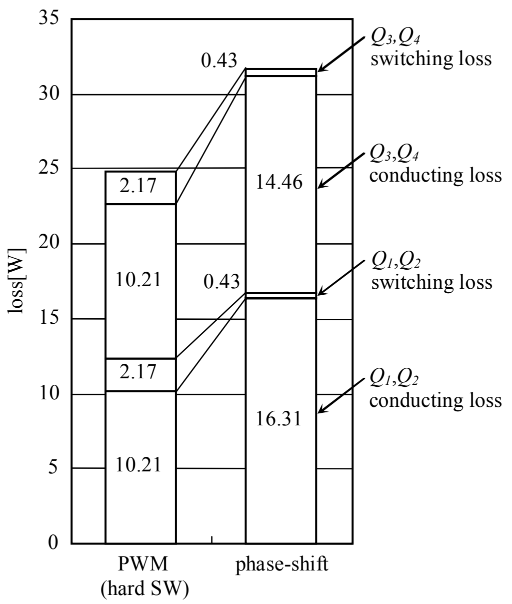


Fig.6. Comparison of losses of the MOSFETs in dc-dc converters controlled by PWM and phase-shift

For comparison, the configuration of a phase-shift soft-switching converter is shown in Fig.4 (rectifier is shown as a conventional type for simplicity) and the principle of the operation is illustrated in Fig.5. ZVS can be easily realized by connecting capacitors to each MOSFET in parallel, and then switching losses are reduced. However, a conducting loss due to a current flowing in the MOSFETs is higher in the zero-voltage period.

In Fig.6, calculated losses in the MOSFET in cases of the PWM and the phase-shift control are compared. (The product number of the employed MOSFET is shown in Table III.) Since the latest MOSFETs have lower switching loss characteristics, the total loss can be reduced in case of the PWM. In phase-shift control scheme, the switching losses are decreased. However, there is no advantage in the total loss in the MOSFETs due to the higher conduction losses. Furthermore, loss in the resonance inductor L_r is generated and primary windings of the transformer T_{r1} is increased additionally if phase-shift control is applied. In consequence, the phase-shift control scheme is not effective for reduction of loss in the specifications.

IV. A Proposal of Another Circuit Configuration of DC-DC Converter

The necessary conditions for using the dc-dc converter depicted in Fig.2 are as follows:

(1) $\hat{v}_{rec}$ at maximum input voltage V_{inmax} is lower than E_d (for keeping $\hat{v}_{rec}<E_d$ in whole variation of V_{in});

(2) $2\hat{v}_{rec}$ at minimum input voltage V_{inmin} is higher than E_d (for guarantee of E_d);

Since $\hat{v}_{rec}$ is in proportion to V_{in}, the ratio V_{inmax}/V_{inmin} has to be less than 2. It is noted that we assume a constant value of E_d.

In cases that the ratio V_{inmax}/V_{inmin} is higher 2, the circuit configuration depicted in Fig.7 could be suitable. In the circuit, a boost chopper is connected to the output of the rectifier. The turns ratio of the T_{r1} should be designed so that $\hat{v}_{rec}$ is slightly lower than E_d at V_{inmax}. The voltage of the snubber capacitor V_s is clamped at E_d, which is always higher than $\hat{v}_{rec}$ so that an unnecessary current through D_s and R_s does not flow. Furthermore, a high voltage rating over 600V for diodes and a series connection of rectifiers such as Fig.2 are not necessary.

In this circuit, we need a boost chopper in cascade additionally compared to the converter in Fig.2. However, a series connection of rectifiers is not necessary. Furthermore, the number of components and number of conducting diodes in the secondary side can be reduced. Moreover, the boost chopper can control E_d. The HF inverter in the primary side then can operate at a fixed duty cycle regardless of the input voltage variation. Therefore, the controller could be simplified.

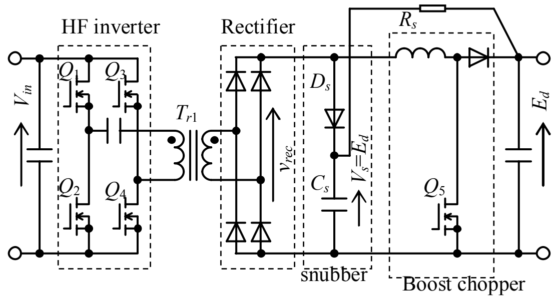


Fig.7. Another circuit configuration of dc-dc Converter

V. Grid-Connected Converter Systems

The circuit configuration of the prototype is depicted in Fig.8. In this system the dc-dc converter depicted in Fig.2 is employed. Table III lists the power semiconductors used in the prototype. IGBTs are used in the inverter because the IGBTs are superior to MOSFETs regarding the reduction of the conduction loss in the specifications. The switching losses in the IGBT are higher than those in MOSFETs. However the switching losses does not influence because the switching frequency is not so high (c.f. Table I).

TABLE III. Power Semiconductors Used in The Prototype

Symbol	Product number	Rating value	Number of parallel connections
Q_1-Q_4	2SK3590-01MR (Fuji Electric)	150V/57A	3
D_1-D_4	ESAD39M-06D (Fuji Electric)	600V/10A, 2in1	1
D_5-D_6	YG912S6 (Fuji Electric)	600V/10A	1
Q_5-Q_8	GT20J301 (Toshiba)	600V/20A	1

Fig.9 and Fig.10 show the external and internal pictures of the prototype. The size of the converter is 219mm × 326mm × 88mm except the air duct. We have minimized the size of converter compared with our conventional converter system (600mm × 700mm × 300mm) having the transformer for the commercial frequencies.

Fig.11 shows the 1kW PEFC unit in which the proposed converter has been employed. Air is respectively forced for cooling the converter and the FC unit, and the air duct for the converter is independently set. For cooling the converter outside air is directly used from the intake and is exhausted to outside via the vent, which prevents the internal temperature rise of the unit.

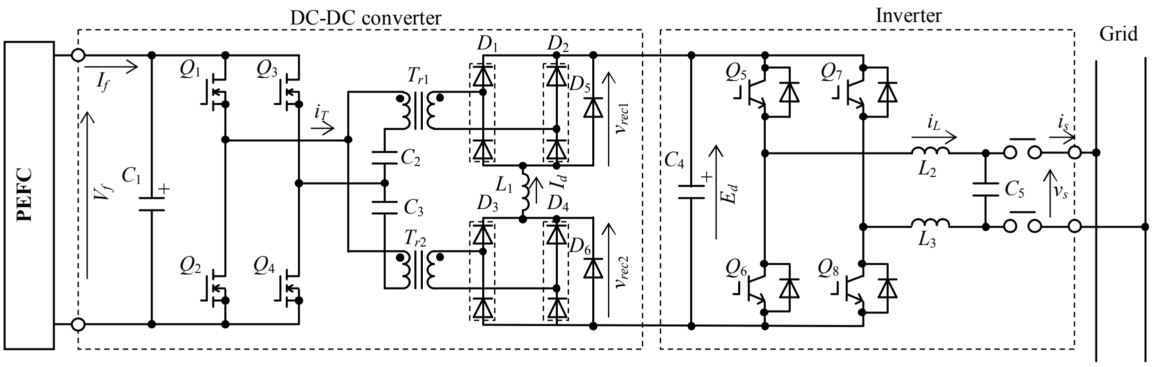


Fig.8. Circuit configuration of Grid-Connected Converter Systems

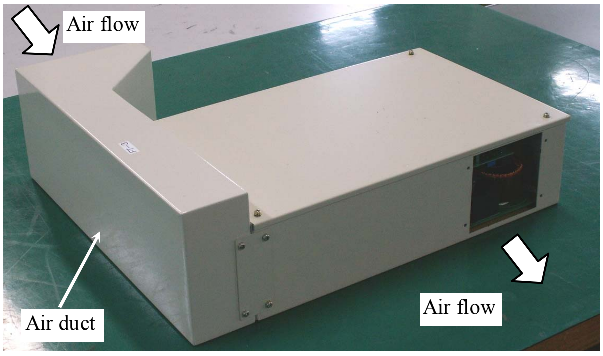


Fig.9. The external appearance of 1kw grid-connected converter

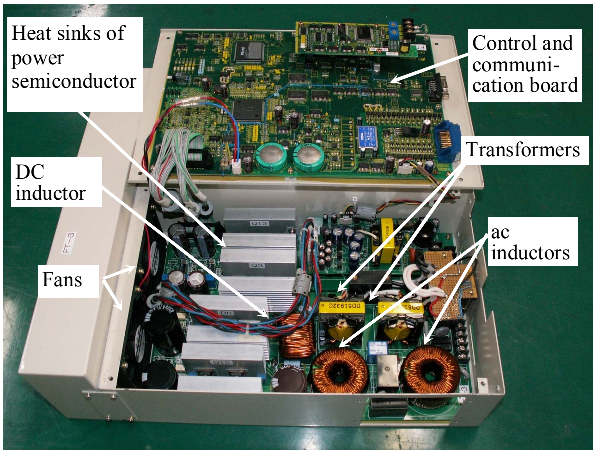


Fig.10. The inside of the converter

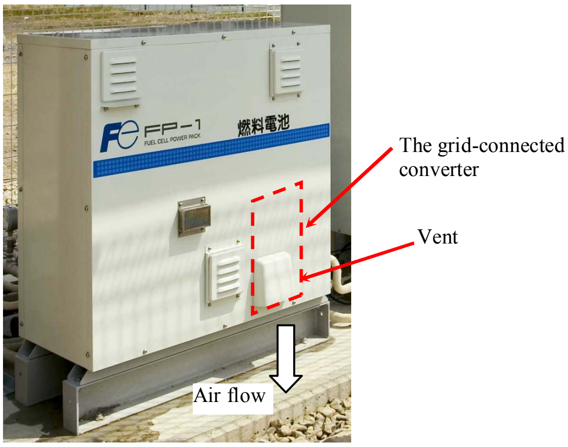
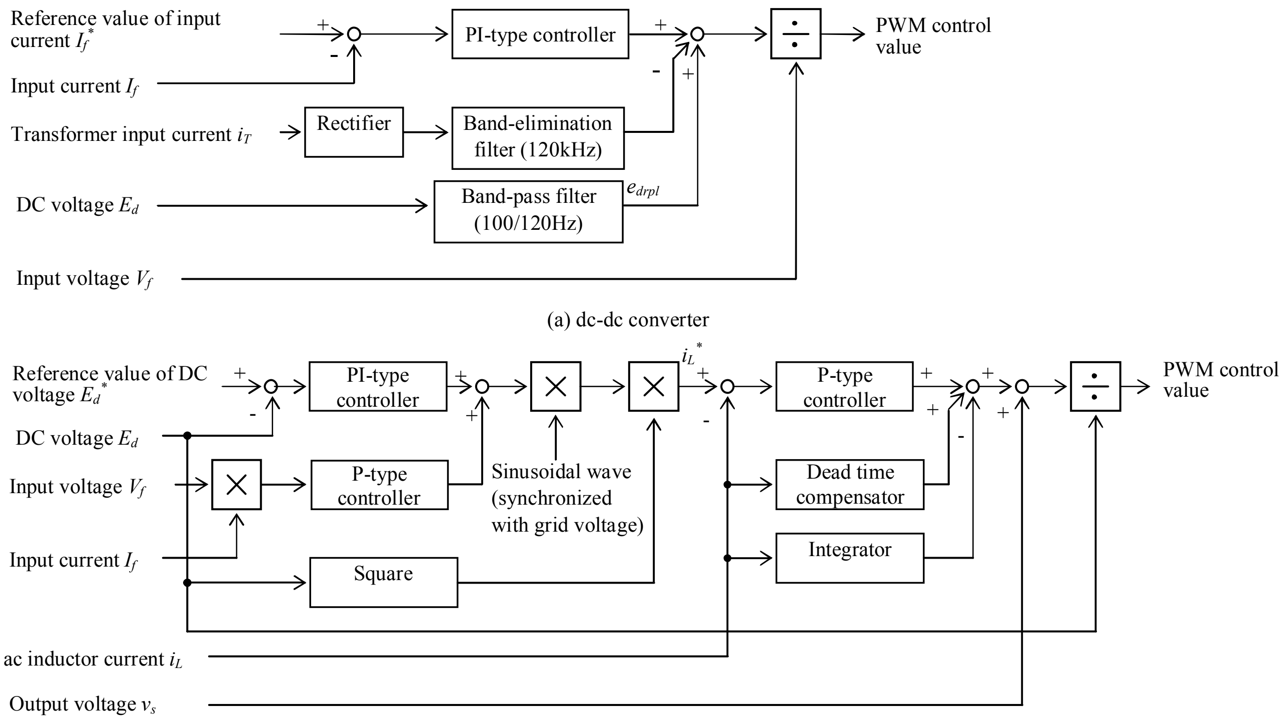


Fig.11. The 1kW PEFC unit including the converter system



(a) dc-dc converter

(b) Inverter

Fig.12. Control block diagrams

VI. CONTROL

Fig.12 shows the control block diagrams of the system. The dc-dc converter is controlled so that the detected input current reaches to the reference which varies depending on the generated power from the PEFC unit. Moreover, the inverter is controlled so that the input power and the output power are equal. E_d is controlled to the reference value in the controller of the inverter. For reducing ripple and any fluctuations of output current I_f of the PEFC we use the feed back control of the primary current i_T of the transformer and the feed forward control of ripple components of E_d. The PI-type controller is employed for controlling I_f. Additionally, variation of the current I_d flowing to L_1 has to be decreased for effectively reducing of ripple components of I_f. In the controller, i_T is controlled instead of I_d because i_T is already detected for the protection of the power devices and I_d can be estimated as the average value of $|i_T|$. Furthermore, ripple components e_{drpl} of E_d varying at 100Hz or 120Hz, which is the double of the output frequency, is detected and the controller of the dc-dc converter works so that half of e_{drpl} is included in v_{rec1} and v_{rec2} respectively. This results in a reduction of a ripple voltage across L_1. Accordingly, I_d is controlled to a constant value by the proposed control circuit, which causes reduction of ripples of I_f.

For achieving an instantaneous current control in the inverter the ac inductor current i_L is detected and controlled by the P-type controller. i_L is then controlled to a sinusoidal shape synchronized with grid voltage v_s.

To eliminate the dc component from the ac output current i_s, the feed back control of i_L performs via the integrator which detects the dc component. i_s is not controlled directly because the phase angle of i_s is delayed due to the low-pass filter (L_2, L_3, and C_5) in the main circuit and the grid impedance. Therefore, a complicated controller could be necessary for the realization of the instantaneous output current control.

VII. EXPERIMENTAL EVALUATIONS

Experimental evaluations at the nominal grid input power (1280W) are shown in Table IV. The test methods and the criteria are based on the interconnection guidelines for distributed generations [3](expect for efficiency). We used the grid reference impedance 0.38Ω+0.45mH with compliance to the standard. Accordingly, the output filter consists of the LC filter in the system and the grid reference impedance, which results in the T-type (L-C-L) filter. The filter can attenuate high frequency current ripples of i_L.

It is verified that the system can fulfill the target values (c.f. TANBLE IV). The input current is controlled to be an almost flat value as can be seen in Fig. 13. The amplitude of the ripple current is 2A (peak to peak value). Moreover, there is no influence of the varying instantaneous power as the single-phase sinusoidal output on the input current. The efficiency of the dc-dc converter is 94.6% at the maximum output power of the PEFC.

Fig.14 and Fig.15 show the anode-cathode voltage waveforms of the rectifier diode. When the spike voltage at the reverse recovery exceeds E_d (365V), the snubber operates to suppress the spike voltage as shown in Fig.15.

Therefore, The peak value of spike voltage is dependent on E_d and almost independent of $\hat{v}_{rec1}$ *and* $\hat{v}_{rec2}$.

The total loss of snubber is around 0.6W, which is calculated with the voltage measurement of the snubber capacitors.

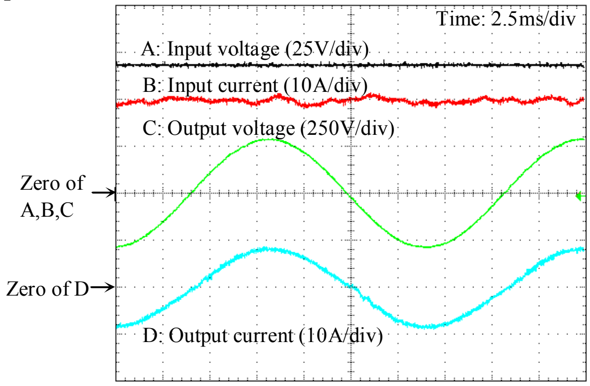


Fig.13. Experimental waveforms of the system

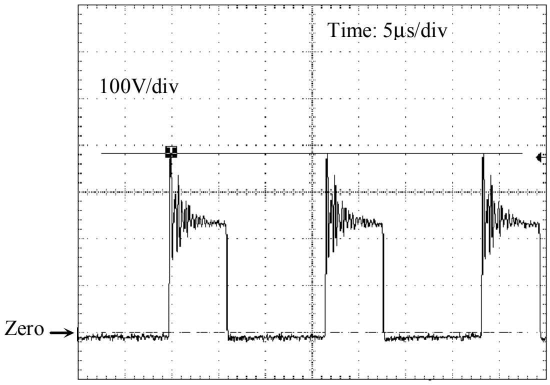


Fig.14. Voltage waveform of rectifier diode (D_1)

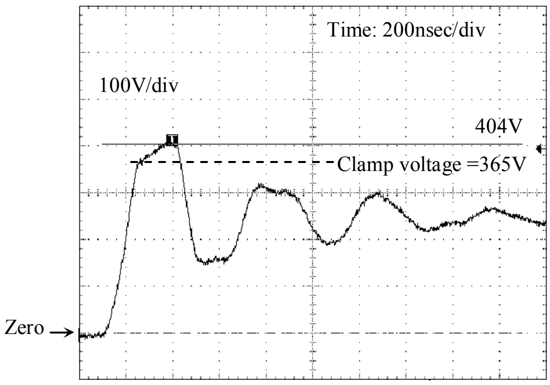


Fig.15. Voltage waveform of D_1 (enlargement of Fig.14)

VIII. Conclusions

A novel circuit configuration of dc-dc converter employed in a grid-connected converter system for PEFC has been proposed in this paper. The control scheme for the system has also been developed. It is verified by a 1kW prototype that low voltage diodes can be used in the rectifiers and the loss in the snubber is reduced.

The size of the prototype is much smaller compared with our conventional products. Furthermore, we confirmed the high efficiency.

It is also verified that the prototype of the system can fulfill the requirements.

References

[1] S. Sumiyoshi, H. Omori, Y. Nakamura, N. Tan, S. Horiuchi and G. Kato, "High efficiency isolated DC-DC Converter with soft switching for Fuel Cell cogeneration system," Proceedings of the 2005 Japan Industry Applications Society Conference, vol.1, pp.349-352 (in Japanese)

[2] R. Yamada, T. Shimizu, K. Kuroki, J. Shinohara, and T. Kagotani, "High-frequency isolation ups with novel SMR," in IEEE IECON, 1993, pp. 1258-1263

[3] Japan Electric Association, JEAG 9701-2001 (in Japanese)

[4] M. Tanitsu, "Snubber Circuit of Insulation Type ac/dc Conversion Device," Japanese Patent Publication number: 09-294373, Date of publication of application: 11.11.1997

[5] M. Hernando, P. Villegas, A. Fernandez, J. Sebastian, and J. Corral, "Design considerations for a 48 VDC to ±400VDC converter for UPS applications, "Power Electronics Specialist Conference, 2003. PESC '03. 2003 IEEE 34th Annual Volume 4, 15-19 June 2003 Pages: 1924 - 1928 vol.4

[6] N, Yoshida, and S, Kondo, "Experimental Result of Power Converter for New Energy Distributed Power Generation System," Proceedings of the 2005 Japan Industry Applications Society Conference, vol.1, pp.437-438 (in Japanese)

[7] J. Garnier, A. De Bernardinis, R. Lallemand, M. C. Péra, G. Coquery, and J. M. Kauffmann, "High Frequency Power Converter for PEFC Generator Architecture based on a Multi Stacks Association for Transportation Applications" Proceedings of the 11th European Conference on Power Electronics and Applications, EPE 2005, Dresden, Germany, Sept. 12 - 14, ISBN: 90-75815-08-5, P.1 - P.10, 2005

TABLE IV. Experimental Evaluations

Item	Criterions	Examination evaluation						
		Grid frequency	50Hz			60Hz		
		Grid voltage	170V	200V	220V	170V	200V	220V
Harmonics of output current	Each component: Under 3%		2.34% (3rd)	2.48% (3rd)	2.59% (3rd)	2.52% (3rd)	2.21% (3rd)	2.52% (3rd)
	Total: Under 5%		2.76%	3.05%	3.53%	2.57%	3.18%	3.62%
Power factor of output	Over 0.95		0.998	0.999	1.000	0.999	1.000	1.000
Converter efficiency	Over 90%		90.61%	91.03%	91.44%	90.52%	91.14%	91.40%