DC to Single-phase AC Voltage Source Inverter with Power Decoupling Circuit based on Flying Capacitor Topology for PV System

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***Abstract*— A novel power decoupling circuit using a flying capacitor topology is proposed in this paper. The inverters, which are connected to a single-phase grid, have single-phase power fluctuation at the twice the grid frequency. Thus, bulky electrolytic capacitor is generally used as DC link capacitor. In the proposed circuit, the power fluctuation is compensated by the flying capacitor in the flying capacitor DC-DC converter. The proposed circuit does not need an additional magnetic component in comparison with the conventional system, which has a boost chopper and an inverter. The proposed converter is experimentally tested with a 1-kW prototype. A voltage ripple at twice the frequency on the inverter DC voltage is suppressed from 35.1% to 4.6%. Moreover, the maximum efficiency of 94.5% with an output power of 1.0 kW is achieved. Finally, the design method of the boost-up inductor for proposed circuit is estimated by experiment. As a result, the error of the ripple current between design and measurement value is 4.7%.**

Keywords—Photovoltaic; grid connected inverter; active power decoupling; flying capacitor DC-DC converter; single-phase power ripple.

I. INTRODUCTION

In recent years, the Photovoltaic (PV) system is active researched as a sustainable power solution. In order to supply the solar power to single-phase grid, a Power Conditioning system (PCS) is used. In general, the PCS is constructed by a boost chopper, and a Voltage Source Inverter (VSI) [1]. The boost chopper is required the function as the boost-up and maximum power point tracking (MPPT). The VSI is needed for the grid connection. However, a conventional system needs the large electrolytic capacitor on DC link due to the single-phase power fluctuation. The electrolytic capacitor has a limited lifetime, approximately less than 7000 hours at 105 degree Celsius operating temperature although the lifetime of a PV panel is namely 25 years. As a result, periodical maintenance is required on the conventional system.

In order to remove the bulky electrolytic capacitor, the active power decoupling method has been studied [2]-[6]. These topologies can reduce the capacitance of the DC link capacitor. However, the extra magnetic components and switching devices are required. These additional components decrease the efficiency, and increase the circuit volume.

On the other hand, the general boost chopper has the large magnetic component as the boost-up inductor for energy buffer. This is because the general boost chopper has to store the energy for boost-up of the input voltage by large inductor only. As a result, the inductance should be designed widely.

In order to reduce the volume of the boost-up inductor, the flying capacitor type DC-DC converter is proposed. The flying topology has the boost-up inductor and flying capacitor, and these components is used for boost-up of the input voltage. In generally, the energy density of the capacitor is large in comparison with the inductor. Thus, the inductance on the flying capacitor DC-DC converter can be reduced more than the general boost-up chopper.

In this paper, a novel power decoupling circuit that uses the flying capacitor topology is proposed in order to solve above mentioned problems. The proposed circuit has the function of the boost-up and single-phase power fluctuation compensation. In the decoupling control strategy, the flying capacitor is charged and discharged at the twice grid frequency. As a results, the single-phase power fluctuation is compensated without the large DC link capacitor. The advantages of the proposed circuit are follows: 1) the additional magnetic component for active power decoupling is not required; 2) the inductance of the boost-up inductor can be reduced in comparison with conventional boost chopper. 3) Simple configuration and easy control.

This paper is organized as follows: first, the configuration of the proposed circuit is shown. Next, the principle of the power decoupling control is described. In addition, the design method of the boost-up inductor is explained, and the inductance between the boost chopper and proposed circuit is estimated. Moreover, the operation of the proposed circuit is demonstrated by the experiment. From the experimental results, the voltage ripple at twice the grid frequency on the inverter

DC voltage is suppressed from 35.1% to 4.6%. Finally, the maximum efficiency of 94.5% with the output power of 1.0 kW is achieved.

II. CIRCUIT TOPOLOGY

A. General configuration of the AC grid connection system

Fig. 1 shows a general configuration of the DC to single-phase AC grid connection system. The input voltage V_{in} is boosted up to more than the peak grid voltage V_{ac} by the boost chopper. When the PV panel is connected to the single-phase grid by VSI, the single-phase power fluctuation which has twice of the power grid frequency in the output side. It is one of the cause to decay the control performance of MPPT. Thus, the large electrolytic capacitor C_{dc} is connected to the DC line, and instantaneous difference power between input and output side is compensated by charge and discharge of C_{dc}. However, the life time of the conventional system is limited by the large electrolytic capacitor.

B. Grid connection system with conventional active power decoupling

Fig. 2 shows the circuit configuration with the conventional active buffer decoupling circuit. In this system, the power decoupling circuit is connected to the DC line instead of the large electrolytic capacitor. This topology is possible to compensate the power fluctuation with small capacitor C_{buf}. Thus, this system is smaller size and longer life-time compared with the conventional circuit in Fig.1. This is because the small film or ceramic capacitor can be used instead of the electrolytic capacitor. However, the additional inductor and switching devices are needed. These components lead to the low efficiency, and increase the circuit volume.

C. Grid connection system with the proposed circuit

Fig.3 shows the grid connection system with the proposed circuit based on flying capacitor DC-DC converter topology [7]. The proposed circuit has capability to compensate the single-phase power fluctuation using the flying capacitor C_{fc} which is controlled for active power decoupling. The advantages of the proposed circuit are follows: 1) Active power decoupling can be achieved without additional magnetic components; 2) the inductance of the boost-up inductor can be reduced in comparison with the general boost-up chopper. Especially, the boost-up operation and power decoupling capability can be achieved by the flying capacitor DC-DC converter. Thus, the total efficiency is improved in comparison with the conventional circuit in Fig.2. This is because the additional circuit for power decoupling is not required in the proposed system.

III. PRICIPLE OF THE ACTIVE POWER DECOUPLING

Fig. 4 shows the principle of the power decoupling operation between the DC and AC sides [8-19]. When both the output voltage and current waveforms are sinusoidal, the instantaneous output power p_{out} is expressed as

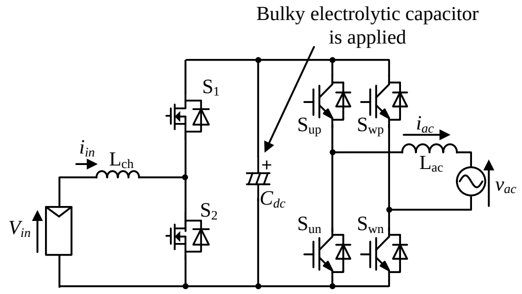


Fig.1. General configuration for DC to single-phase AC grid connection system. This circuit has a large electrolytic capacitor C_{dc} on the DC link part. C_{dc} is usually used the bulky electirolytic capacitor.

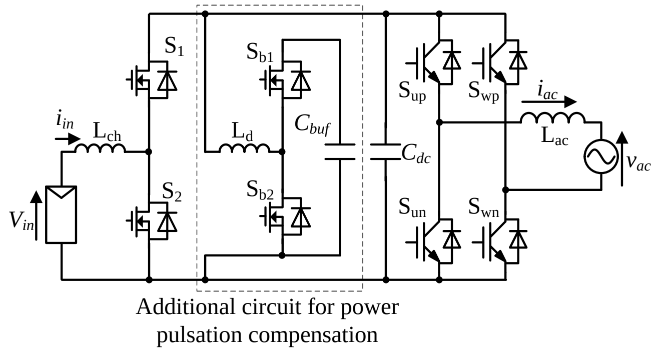


Fig.2 Power conditioner system using the conventional active power decoupling method. This circuit needs an additional inductor and switching devices. It cause low efficiency and large circuit volume.

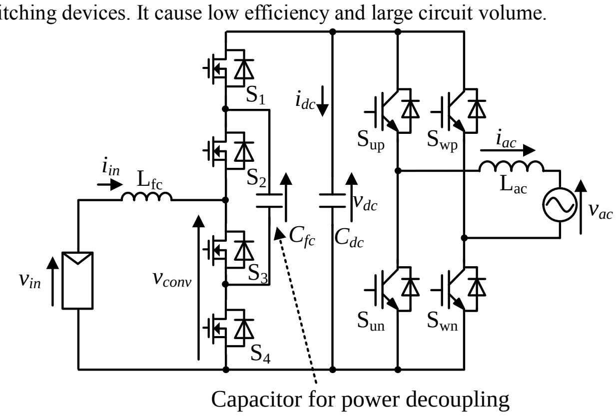


Fig.3. Proposed circuit using the flying capacitor DC-DC converter topology. This circuit use the flying capacitor C_{fc} in order to compensate the single-phase power fluctuation. Thus, the additional component is not needed.

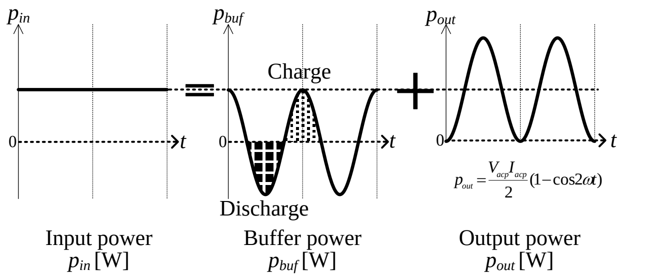


Fig.4. Compensation principle of the single-phase power fluctuation. The power ripple that contains frequency twice of the grid frequency appears at DC link voltage. In order to compensate the power fluctuation at input DC side, buffer power p_{buf} is fluctuated by flying capacitor C_{fc}.

$$p_{out} = \frac{V_{acp} I_{acp}}{2}(1 - \cos 2\omega t) \tag{1}$$

Where, V_{acp} is the peak voltage, I_{acp} is the peak current, and ω is the angular frequency of the output voltage. From (1), the power ripple, that contains twice frequency of the power grid, appears at DC link.

In order to absorb the power ripple, the instantaneous power p_{buf}, should be controlled by

$$p_{buf} = \frac{1}{2} V_{acp} I_{acp} \cos 2\omega t \tag{2}$$

where, the polarity of the p_{buf}, is defined as positive when the flying capacitor C_{fc} discharges. Note that the active power of the flying capacitor C_{fc} is zero. Due to the power decoupling, the input power is matched to the output power. Thus, the relationship between the input and output power is expressed as

$$p_{in} = \frac{1}{2} V_{acp} I_{acp} = V_{IN} I_{IN} \tag{3}$$

IV. CONTROL STRAGEGY FOR THE PROPOSED CIRCUIT

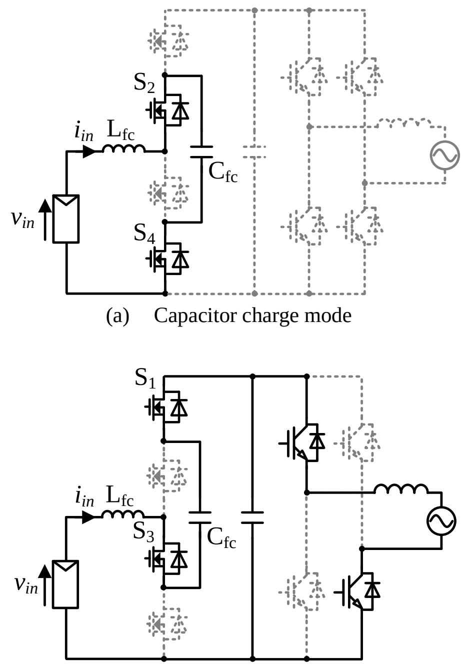
Fig.5 shows the operation mode of the flying capacitor DC-DC converter. The flying capacitor C_{fc} is charged or discharged for boost-up and compensation of the power fluctuation. In the proposed control, each switching duty is decided by relationship between input and output power in Fig.1. When the input power is large in comparison with the instantaneous output power, the on duty of charge mode set widely. On the other hand, when the input power is small, the on duty of discharge mode should be set widely.

Fig.6 shows the control block diagram for the flying capacitor DC-DC converter. In the proposed control, the Automatic Current Regulator (ACR) and Automatic Voltage Regulator (AVR) are implemented to control the generative power P_{in} of PV and charge or discharge of C_{fc}. Note that, P_{in} is controlled by MPPT, and the input current i_{in}^* is calculated at the maximum power point. Thus, the input current i_{in} is regulated on the maximum power point by ACR.

In the flying capacitor control, the flying capacitor voltage v_{fc} is controlled to vary at the twice of the grid frequency in order to compensate the single-phase power fluctuation by AVR. The voltage reference v_{fc}^* is expressed as

$$v_{fc}^* = \sqrt{\left(\frac{v_{dc}}{2} - \frac{p_{out}}{\omega C_{fc} V_{dc}}\right)^2 - \frac{p_{out}}{\omega C}\{\sin(2\omega t) - 1\}} \tag{4}$$

where, v_{dc} is the DC link voltage, p_{out} is the output power, C_{fc} is the capacitance of the flying capacitor, ω is the angular frequency. From the flying capacitor voltage control, the power



(a) Capacitor charge mode

(b) Capacitor discharge mode

Fig.5. Operation mode of the flying capacitor DC-DC converter. In order to achieve the power decoupling, each duty period is adjusted by the single-phase power fluctuation.

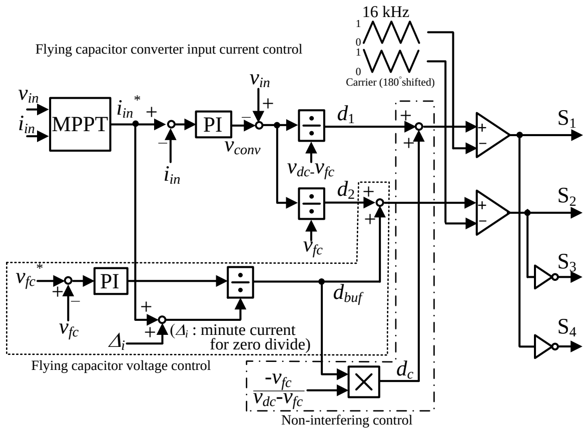


Fig.6. Control block diagram for the flying capacitor DC-DC converter. This is circuit is controlled based on the input curren and flying capacitor voltage control.

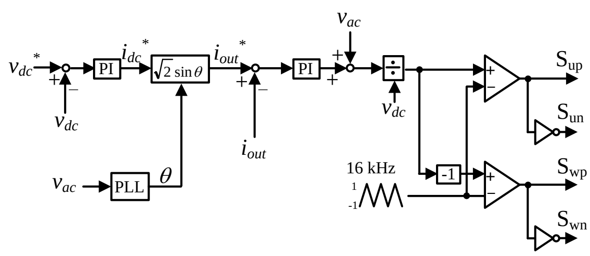


Fig.7. Control block diagram for VSI. The inverter output current control and DC link voltage control is applied for grid connection.

fluctuation compensation duty reference d_{buf} is calculated. Note that, the switching signal S_1 to S_4 is decided by the some duty reference and triangle waveform on the modulation part. However, d_{buf} interfere with the control performance of ACR. As the results, the input current is fluctuated at the twice of the single-phase grid frequency. In order to solve this problem, the control decoupling reference d_c is added. The d_c is expressed as

$$d_c = -\frac{v_{fc}}{v_{dc} - v_{fc}} d_{buf} \tag{5}$$

Fig.7 shows the control block diagram of the VSI. In order to control the DC link voltage V_{dc}, reference value of AVR is set more than the grid voltage. Finally, the Phase Looked Loop (PLL) is applied to ensure that the phase angle of the inverter output current is identical to the grid.

V. COMPONENT DESIGN FOR PROPOSED CIRCUIT

A. Flying capacitor C_{fc}

The flying capacitor C_{fc} is designed from p_{out} which is the electric storage energy to compensate the power fluctuation. The C_{fc} is expressed as

$$C_{fc} = \frac{2P_{out}}{\omega(V_{c\max}{}^2 - V_{c\min}{}^2)} \tag{6}$$

where, P_{out} is output power, V_{cmax} is maximum flying capacitor voltage, V_{cmin} is minimum flying capacitor voltage, ω is the angular frequency. In order to reduce the C_{fc}, the difference value between V_{cmax} and V_{cmin} should be set widely. In other words, the peak voltage increase. Thus, C_{fc} is needed to design less than the blocking voltage.

B. Boost-up inductor L_{fc}

The boost-up inductor L_{fc} is generally designed from ripple current of the inductor current i_L. In the conventional circuit, it is easy to design the boost-up inductor because the duty reference and peak to peak value of the ripple current is constant. However, the duty reference is not constant in the proposed circuit. This is because the flying capacitor voltage v_{fc} is fluctuated in order to achieve the active power decoupling. It is mean the duty reference and peak to peak value of the ripple current swing. Thus, in the proposed circuit, the boost-up inductor L_{fc} is designed when the current ripple is maximum value.

When the active power decoupling is not applied, the inductance of L_{fc} is expressed as

$$L_{fc} = \alpha \frac{V_L}{4 f_{sw} \Delta I} \tag{7}$$

where, α is the duty ratio, V_L is inductor voltage, f_{sw} is the switching frequency, ΔI is the ripple ratio of the inductor current. In comparison with the boost-up chopper, the inductance of the flying capacitor DC-DC converter can be designed by one quarter. This is because the ripple current frequency become the twofold of the switching frequency, and the flying capacitor voltage V_{fc} is controlled at the half of DC link voltage V_{dc}. However in the proposed circuit, the duty ratio and the V_L is swung due to the power decoupling control. Thus, the boost-up inductor of the proposed circuit is designed by the some duty reference d_1 and d_2 [20].

The duty reference of the d_1 and d_2 are expressed as

$$d_1 = \frac{V_{in}}{V_{dc}} \{1 - \cos(4\pi f t)\} \tag{8}$$

$$d_2 = \frac{V_{in}}{V_{dc}} \left\{1 + \left(\frac{V_{dc}}{v_{fc}} - 1\right)\cos(4\pi f t)\right\} \tag{9}$$

where, the duty reference d_1 and d_2 is included the frequency component. This is given by the power decoupling duty d_{buf} and the control decoupling reference d_c. From the equation as (8) and (9), the boost-up inductor of the proposed circuit is

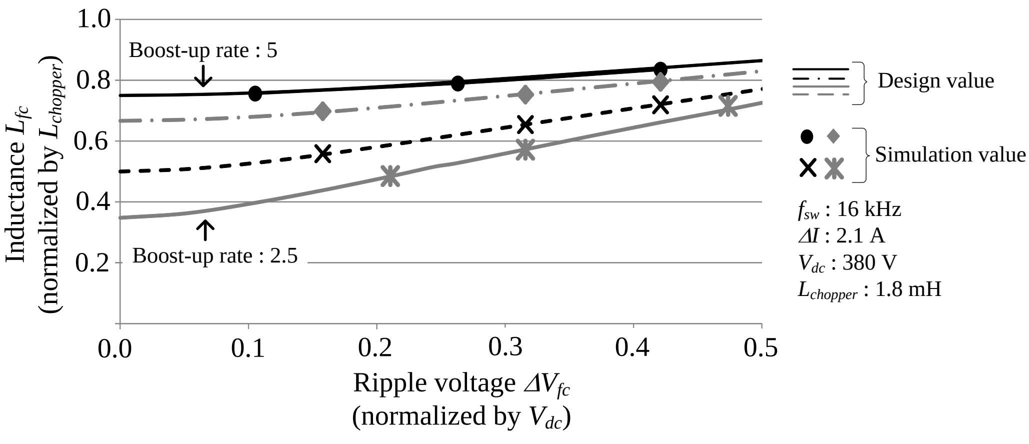


Fig.8 Relationship between the ripple voltage of the flying capacitor and inductance of the boost-up inductor.

expressed as

$$L_{fc} = \frac{\max\left[\max\left\{\left(V_{dc} - v_{fc} - V_{in}\right)d_1\right\}, \max\left\{\left(v_{fc} - V_{in}\right)d_2\right\}\right]}{f_{sw}\Delta I} \quad (10)$$

Fig.8 shows the relationship between the boost-up inductor and ripple voltage. Where, the switching frequency f_{sw} is 16 kHz, DC link voltage V_{dc} is 380 V, the ripple current ΔI is 2.1 A, and the inductance of the general boost-up chopper is 1.8 mH. In order to consider the validity of the designing equation by (10), the design value and simulation results are estimated. In addition, the boost-up rate is changed from 2.5 to 5. Moreover, the boost-up inductor L_{fc} is normalized by the inductance of the boost-chopper $L_{chopper}$.

According to Fig.8, the design value and simulation result are also matched. Thus, the validity of the design for boost-up inductor is checked. In addition, the inductance rate is under than 1p.u. at the all conditions. It is mean the boost-up inductor can be design under than the inductance of the general boost-up chopper. Moreover, the boost-up inductor can be most reduced when the boost-up ratio is 2.5. This is because a lot of energy for boost-up is needed when the boost-up ratio is high. Finally, when the peak to peak voltage of the flying capacitor ΔV_{fc} is increased, the boost-up inductor L_{fc} become large. This is because the buffer power for the single-phase power fluctuation is increased.

VI. SIMURATION AND EXPERIMENT

A. Simularion result

In this chapter, the validity of the single-phase power fluctuation compensation is revealed by the simulation.

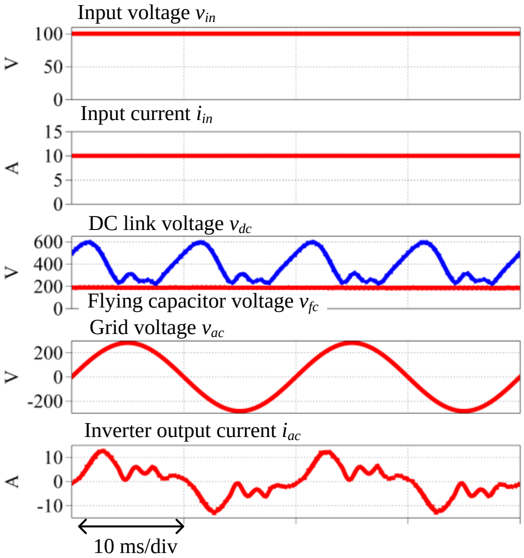
Table 1 shows the simulation parameter. Fig.9 shows the simulation results of the proposed circuit. In the simulation, the operation of MPPT is not estimated. The rated power of the proposed circuit is 1 kW, and the large capacitor is not set to the simulation parameter.

Fig.9 (a) shows the operation waveform without the power decoupling operation. According to Fig.9 (a), the DC link voltage v_{dc} and inverter output current i_{ac} are distorted by the single-phase power fluctuation. In the proposed circuit, the capacitance of the DC link capacitor C_{dc} is small. Thus, when the single-phase power fluctuation is not compensated, the DC link voltage v_{dc} is included the twice grid frequency component. As a result, the controlled performance for the inverter output current control is decayed. From these reason, the bulky electrolytic capacitor is needed on the DC link part in the conventional circuit. Due to use the electrolytic capacitor, the life-time is limited. In addition, the circuit volume is increased.

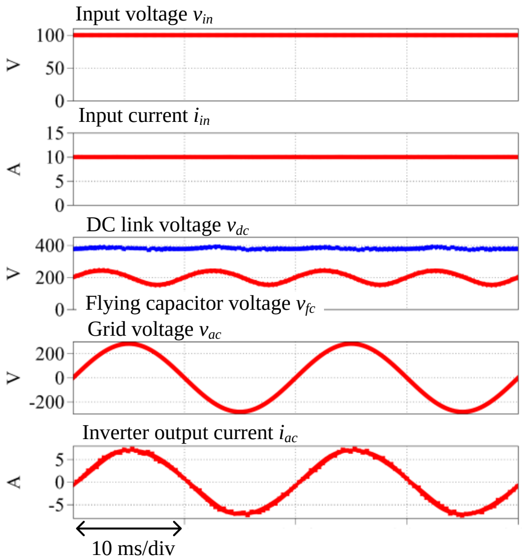
Fig.9 (b) shows the operation waveform with the power decoupling operation. According Fig.9 (b), the DC link ripple voltage is reduced by 96.2%. In addition, the flying capacitor voltage v_{fc} is fluctuated by the twice grid frequency. Moreover, the flying capacitor average voltage is balanced at the half value of the DC link voltage. Finally, the inverter output

Table.1 Simulation parameter

Input voltage	V_{in}	100 V
Input current	I_{in}	10 A
Switching frequency	f_{sw}	16 kHz
Flying capacitor	C_{fc}	180 μF
DC link capacitor	C_{buf}	20 μF
Boost-up inductor	C_{filter}	2 mH
Grid voltage	$v_{\_grid}$	200 V_{rms}
Grid frequency	$f_{\_grid}$	50 Hz
Output power	P_{out}	1 kW
Angular frequency for ACR	ω_{nacr}	4000 rad/s
Angular frequency for AVR	ω_{navr}	400 rad/s



(a) Without power decoupling



(b) With power decoupling

Fig.9 Simulation result of the proposed circuit.

current becomes sinusoidal waveform. From these results, the single-phase power ripple is compensated with the small capacitor. Especially, the proposed circuit is not required the additional circuit and electrolytic capacitor in order to compensate the power decoupling.

Fig.10 shows the harmonic analysis result of the DC link voltage V_{dc}. According to Fig.10, the second order harmonic component is reduced by 82.1% compared to the without power decoupling. Thus, the single-phase power fluctuation is compensated. The reason that the second order harmonic component exist is because; (i) the compensation value is not enough at 1 kW (ii) the phase of the buffer power for single-phase power fluctuation compensation is not matching to the single-phase power grid. This will be improved in the future work.

B. *Experimental result*

In order to demonstrate the validity of the proposed circuit, a 1 kW class prototype circuit is tested. Fig. 11 show the experimental results in order to confirm the availability of the proposed decoupling control. In this experiment, MPPT control is not introduced for simplicity.

According to Fig. 11 (a), the input current i_{in} is constant. However, the inverter DC voltage v_{dc} is fluctuated at twice of the single-phase grid frequency. This is because the instantaneous difference value between input and output power is compensated by the DC link capacitor C_{dc}. As a result, the Total Harmonic Distortion (THD) of the output current i_{ac} is increased.

According to Fig. 11 (b), the flying capacitor voltage v_{fc} is fluctuated by the proposed control, and the v_{dc} is constant. From the results, the single-phase power fluctuation is compensated by the flying capacitor C_{fc}. In addition the flying capacitor average voltage is balanced at the half value of the DC link voltage. Finally, the output current i_{ac} became a sinusoidal waveform by the proposed control. Especially, the proposed circuit can achieve the active power decoupling without the additional circuit. Thus, the efficiency and power density can be improved.

Fig.12 shows the harmonic analysis of the DC link voltage. The second order harmonic component is reduced by 89.9% compared to without the power decoupling control. However, the second order harmonic component is still included on the DC link voltage. This is because the power fluctuation compensation value has the error by the actual single-phase power fluctuation.

Fig.13 shows the efficiency characteristics of the proposed circuit. From this result, maximum efficiency is 94.5% when the output power is 1 kW. However, the efficiency at the light load decrease. In order to improve the efficiency, the loss analysis for the proposed circuit is conducted.

Finally, the ripple current of the boost-up inductor is estimated. Fig.14 shows the ripple current ΔI. In this experiment, peak to peak value of the ripple current ΔI is designed at 2.1 A. In addition, the inductance of the boost-up inductor L_{fc} is designed from equation as (10). As a result, the

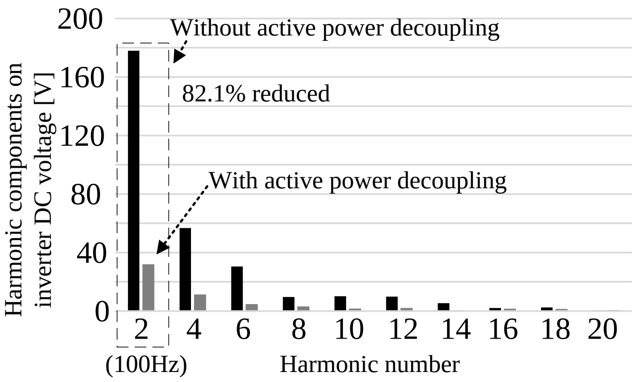
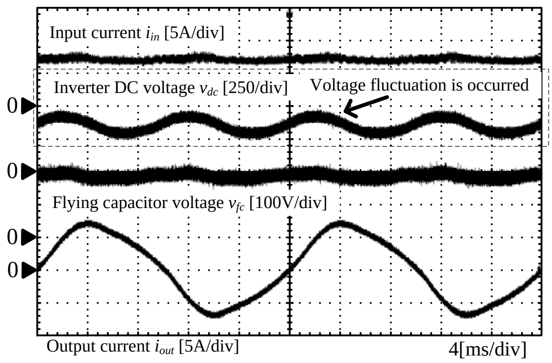


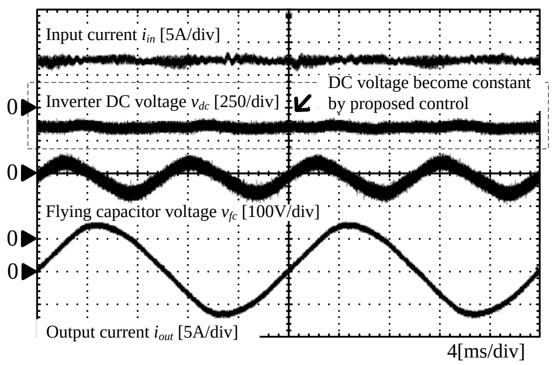
Fig.10 Harmonic analysis result in simulation.

Table.2 Experimental parameter

Switching frequency	f_{sw}	16 kHz
Capacitances	C_{fc}	180 μH
	C_{dc}	60 μH
Inductances	L_{fc}	2 mH
	L_{ac}	2.8 mH (%Z=2.3%)
Input voltage	V_{in}	150 V
Inverter DC voltage	V_{dc}	300 V
MOSFETs	S_1-S_4	IXYS, IXFN132N50P3
IGBTs	S_{up}, S_{un} S_{vp}, S_{vn}	Fuji electric, 2MBI100VA



(a) Without power decoupling



(b) With power decoupling

Fig.11 Experimental result

error between the actual and design value is 4.7%. Therefore, the validity of the design method is demonstrated by experiment.

VII. CONCLUSION

In this paper, the novel power decoupling circuit that uses the flying capacitor topology is proposed in order to solve above mentioned problems. The proposed circuit has the function of the boost-up and single-phase power fluctuation compensation. In the decoupling control strategy, the flying capacitor is charged and discharged at the twice grid frequency. As a results, the single-phase power fluctuation is compensated without the large DC link capacitor. The advantages of the proposed circuit are follows: 1) the additional magnetic component for active power decoupling is not required; 2) the inductance of the boost-up inductor can be reduced in comparison with conventional boost chopper. 3) Simple constitution and easy control. In addition, the validity of the single-phase power fluctuation compensation is revealed by the simulation and experiment.

From the experimental results, the flying capacitor v_{fc} voltage is fluctuated by the proposed control, and v_{dc} is constant. From the results, the single-phase power fluctuation is compensated by the flying capacitor C_{fc}. In addition the flying capacitor average voltage is balanced at the half value of the DC link voltage. Finally, the output current i_{out} became a sinusoidal waveform by the proposed control. Especially, the proposed circuit can achieve the active power decoupling without the additional circuit. Thus, the efficiency and power density can be improved.

In future works, the converter loss will be estimated in order to improve the efficiency. In addition, optimization of the switching frequency will be estimated. Moreover, the power density both the conventional circuit and proposed circuit will be compared.

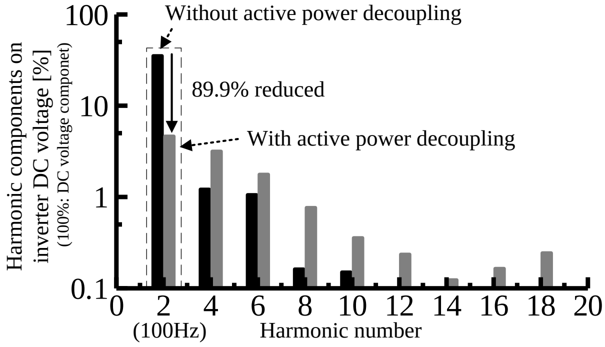


Fig.12 Harmonic analysis result in experiment.

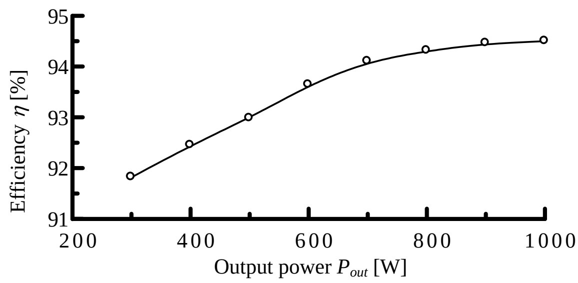


Fig.13 Efficiency characteristics.

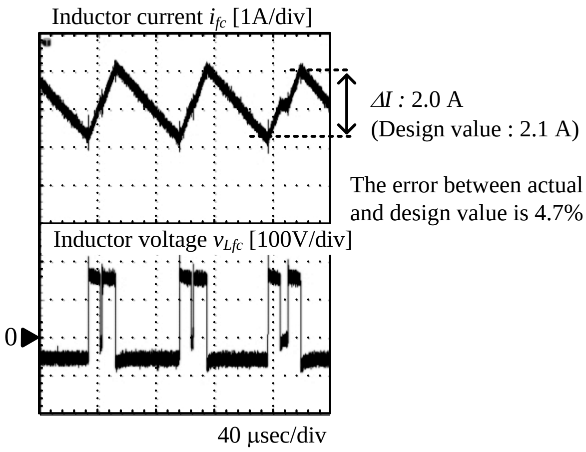


Fig.14 Estimation of the ripple current of the boost-up inductor.

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