Switching Loss Reduction of AC-AC Converter using Three-level Rectifier and Inverter for UPS.

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***Abstract*— This paper proposes an AC-AC converter, which consists of T-type three-level rectifier and inverter, for an on-line UPS. The switching loss of the proposed AC-AC converter is drastically reduced because the proposed converter is driven at a very low switching frequency which is six times of input side frequency. The T-type rectifier separates the maximum phase-voltage, medium phase-voltage and minimum phase-voltage from the input voltage. Next the output waveform is built by the T-type inverter from each maximum phase-voltage, middle phase-voltage and minimum phase-voltage. The proposed circuit can achieve not only high efficiency, but also short instantaneous interruption time. Furthermore, the proposed AC-AC converter compensates a voltage dip with changing an operation mode of a rectifier. In this paper, the fundamental operation of the proposed converter is confirmed by simulations and experiments. In addition, the power loss of the proposed converter is compared to a conventional on-line UPS and the efficiency of the proposed converter is 97.1% at rated load in an experiment.**

Keywords*— Uninterruptible power systems; Power electronics; Circuit topology; Modulation; Power conversion; voltage dip; AC-AC converter

I. INTRODUCTION

Recently, the demand of uninterruptible power supplies (UPS) for many server rooms and line factories has been increased [1]. Due to the use of UPSs, the stability of power sources has increased and the damage on instantaneous power failure such as a data loss in data centers or a halt of the production in factories is avoided. The configurations of UPSs are divided into a standby type and an on-line type. The standby type has an advantage that when a grid is in a normal state, a provided current flows only through AC switches. Therefore the power loss is very small. However, when the grid fails, the detection of the voltage drop takes several ms and the load voltage is interrupted during the detection period [2]. On the other hand, the on-line type provides no interrupted power even if the grid fails because the on-line type UPS operates constantly. However, this operation requires a PWM control which generates switching loss even when the grid is in the normal state. In order to solve the problem, a method that reduces the switching loss by increasing levels of the converter and reducing rating voltages of switching devices has been proposed [3-5]. This method is also effective for UPS application [6]. However, the use of a PWM control implies a high switching frequency. Therefore the reduction of the switching loss at a stable grid condition is limited.

This paper proposes an AC-AC converter using T-type three-level converters in order to reduce the switching loss. The proposed converter is driven at six times of the grid frequency. In addition, when the grid voltage decreases, the rectifier in the proposed converter is controlled as a boost mode with PWM operation. As a result, a constant output voltage is maintained. Moreover, the load power is supplied from a battery through the proposed converter without a voltage drop during interruption of the power grid. Therefore, the proposed converter is appropriate for an on-line type UPS because the proposed converter reduces the switching loss in the stable operation of the grid and compensates the grid failure. Additionally, the proposed converter has high reliability and long lifetime because the proposed converter uses film capacitors at a DC-link instead of any electrolytic capacitors.

This paper is organized as follows. Firstly a control method and operations of the proposed converter are described; secondly, simulation results for the stable operation, the voltage dip and the interruption of the grid are presented. As a result of a loss analysis, the proposed converter obtains an efficiency of 97.7% while an efficiency of a conventional on-line UPS is 94.6%. Finally, experimental results for the stable operation are presented. An efficiency of 97.1% is confirmed by an experimental result at 3 kW load.

II. SYSTEM CONFIGURATION

A. Conventional UPS circuits

Fig. 1 shows conventional circuit configurations for UPSs. Fig. 1(a) shows the standby type while Fig. 1(b) shows the on-line type. In the standby type, when the grid is stable, the power is supplied to the load from the grid through AC switches. Therefore, the power loss is very low. When the grid fails, the AC switches are opened and the inverter in the UPS starts to operate. As a result, the load power is supplied from the battery by the inverter. However, there is an interruption time of several ms at changing the operation mode.

On the other hand, on the on-line method, CVCF (constant voltage constant frequency) power is supplied to the load by using a rectifier and an inverter. Therefore, the interruption time of this method is zero, and the on-line type UPS is used for applications that require high reliability. However, there is a problem in this method, which the PWM control of the rectifier and the inverter are needed regardless of the grid condition. Therefore, the switching loss is generated at all the time.

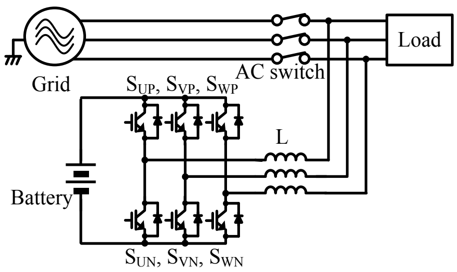
B. *Proposed UPS circuit*

Fig. 2 shows the proposed circuit diagram. The proposed circuit consists of a three-phase three-level T-type AC-DC-AC converter [7], [8], batteries and a buck chopper. The proposed converter has no large electrolytic capacitors because the proposed method utilizes a voltage ripple at six times of the grid frequency (300 Hz) in a DC-link voltage. This also results in reducing the switching loss significantly. Specifically, the maximum voltage v_{max}, the medium voltage v_{mid} and the minimum voltage v_{min} in the input three-phase voltage are connected to p, o and n points in the DC-link without a smoothing by the rectifier. It should be noted that bidirectional switches of the rectifier turns on to conduct v_{mid} whereas the diode bridge selects v_{max} and v_{min} automatically. Finally, a three-phase voltage is provided to the load by the inverter which turns each 60 degrees of an output voltage phase. Therefore, the proposed converter reduces the switching loss drastically when the grid condition is stable. In addition, when the grid voltage is decreased, the rectifier boosts up the input voltage and the DC-link voltage. As a result, the output voltage is maintained at constant. Moreover, for an interruption of the grid, the load power is supplied from the battery through the buck chopper and the inverter without any voltage drop.

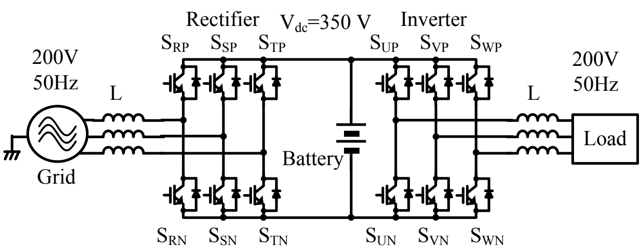
III. Control Method

A. *CVCF control with switching each 60 degrees for a stable grid condition*

Fig. 3 shows a control block diagram when the grid is stable. Fig. 4 shows the correspondence of input voltage phase and a variable that is used for the judgment of the control area



(a) Standby type.



(b) On-line type.

Fig. 1 Conventional circuits for UPS.

(*state number*). Table 1 shows a switching table of the rectifier and the inverter. In Fig. 3, the rectifier and inverter of the proposed circuit are driven by open loop control using *state number* to decide switching patterns. In Fig. 4, *state number* is determined along a magnitude relation of the input phase voltage v_r, v_s and v_t. The *state number* changes each 60 degree of the input voltage phase and switching patterns of the rectifier and the inverter are decided by referring *state number* and Table 1. It should be noted that P1 and P2 in Table 1 are switching signals for the voltage dip only, and these are set to 0 during the stable grid condition.

B. *Power supply method using batteries for interruption*

In the proposed circuit, the output power is supplied from the batteries by the buck chopper when the interruption occurs. The buck chopper is connected at the DC-link in parallel with

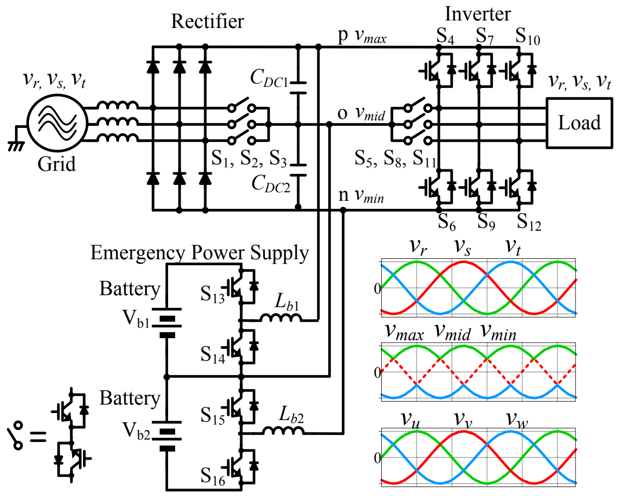


Fig. 2. Proposed AC-AC converter for UPS.

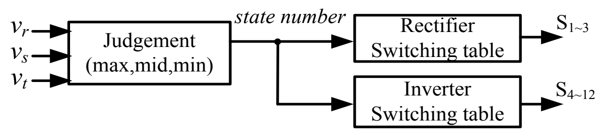


Fig. 3. Control block diagram of CVCF.

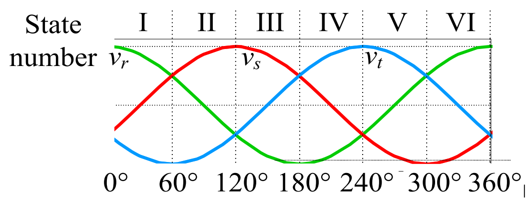


Fig. 4. Correspondence of input voltage to state number.

TABLE I. Switching Table of AC-AC Converter Control.

Rectifier

state no.	S1	S2	S3
I	P1	1	P2
II	1	P1	P2
III	P2	P1	1
IV	P2	1	P1
V	1	P2	P1
VI	P1	P2	1

Inverter

state no.	S4	S5	S6	S7	S8	S9	S10	S11	S12
I	1	0	0	0	1	0	0	0	1
II	0	1	0	1	0	0	0	0	1
III	0	0	1	1	0	0	0	1	0
IV	0	0	1	0	1	0	1	0	0
V	0	1	0	0	0	1	1	0	0
VI	1	0	0	0	0	1	0	1	0

the rectifier. Hence, in order to compensate the interruption without changing the 60 degree switching operation of the inverter, the buck chopper needs to output the DC voltage with a ripple of 300 Hz during the interruption as well as the normal condition. Specifically, the DC-link voltage v_{max}-v_{mid} and v_{mid}-v_{min} are controlled by the buck chopper. Then, the output voltage of the chopper is controlled by the following equations.

$$v_{\max} - v_{mid} = d_{13} V_{b1} \tag{1}$$

$$v_{mid} - v_{\min} = d_{16} V_{b2} \tag{2}$$

$$d_{14} = 1 - d_{13} \tag{3}$$

$$d_{15} = 1 - d_{16} \tag{4}$$

Where, d_{13}, d_{14}, d_{15}, d_{16} are the duty ratio of the S_{13}, S_{14}, S_{15}, S_{16}.

C. Voltage dip compensation

Fig. 5 shows an equivalent circuit of the rectifier used for the compensation of the voltage dip of the grid. From Fig. 5, the rectifier is able to be assumed as a boost up rectifier. Hence, for the compensation, two bidirectional switches at v_{max} and v_{min} carry out PWM operation in order to boost up the decreased input voltage.

Fig. 6 shows a control block diagram for the grid voltage dip compensation. In Fig. 6, a boost up ratio is calculated by using the amplitudes of the input voltage vector and the output voltage reference vector. The boost up ratio is modulated by a carrier comparison method with a triangle wave. Finally, the switching signal P1 and P2 is used for the voltage dip compensation.

IV. Simulation Results

A. Input and Output waveforms

In order to confirm the fundamental operation of the proposed circuit, this chapter shows simulation results using the simulator PLECS (*Plexim*). Table 2 shows simulation conditions of the proposed circuit. The input voltage and the input frequency are set to 200 V, 50 Hz, sinusoidal waveform. The load is an RL-load of 1-5 kW.

Fig. 7 shows operation waveforms of the CVCF control. In these results, it is confirmed that the output voltage of 200 V, 50 Hz is achieved by regulating the DC link voltage at 300 Hz even when the switches are driven at a very low frequency of 300 Hz.

Fig. 8 shows operation waveforms when an interruption is emulated by decreasing the input voltage to zero suddenly. It should be noted that a detection method of the interruption in [9] is used. From Fig. 8, the proposed converter supplies power to the load by maintaining the DC-link voltage even if the input voltage becomes zero suddenly due to the interruption. In addition, the proposed converter changes the current pathway from the grid to the battery without output voltage drop in the same manner with the conventional on-line type UPS. It should be noted that the output voltage oscillates by 22% at the interruption because of a resonance between inductors L_{b1}, L_{b2} of the buck chopper and the DC-link capacitor C_{DC1}, C_{DC2}.

Fig. 9 shows operation waveforms when a voltage dip is emulated by decreasing the input voltage to 0.5 p.u. suddenly. From Fig. 9, the proposed converter maintains the output voltage of 200 V, 50 Hz because the rectifier boosts up the decreased input voltage with the voltage dip compensation method.

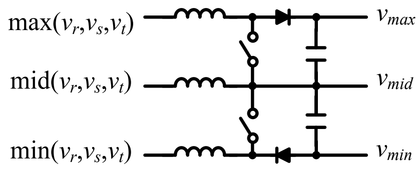


Fig. 5. Equivalent circuit of rectifier at the grid voltage dip compensation.

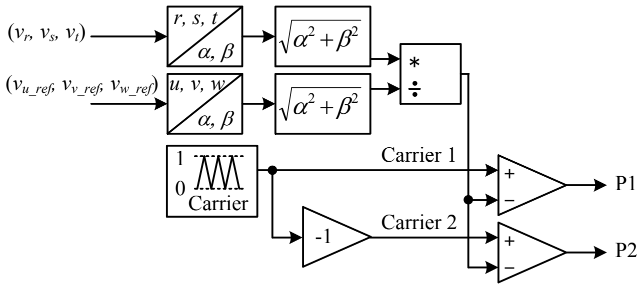


Fig. 6. Control block diagram of the grid voltage dip compensation.

TABLE II. Simulation conditions of the proposed circuit model.

Input line voltage	200V(rms)	Rated output voltage	200V(rms)
Rated power	3 kW	Load resistance	13 Ω
grid frequency	50 Hz	Load inductance	1 mH
Input inductance	0.1 mH	V_{b1}, V_{b2}	300V
L_{b1}, L_{b2}	0.1 mH	C_{DC1}, C_{DC2}	1 uF
CVCF control	switching frequency		300 Hz
Buck chopper control	switching frequency		100 kHz
Boost mode control	switching frequency		100 kHz
	input line voltage step		-0.5 p.u.

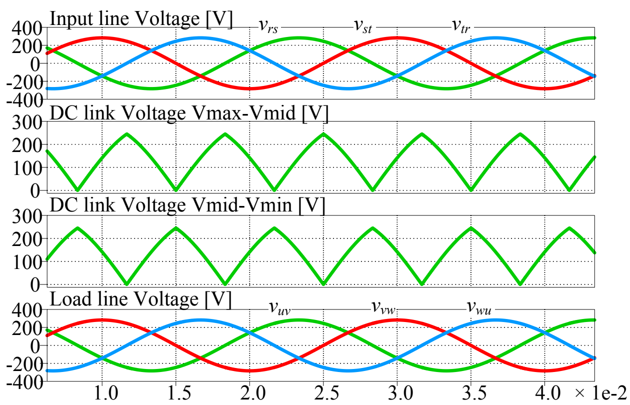


Fig. 7. Operation waveforms of the proposed circuit by simulation when the grid is not fail.

B. Loss analysis

In order to confirm the validity of the proposed converter from the viewpoint of the efficiency, this section compares the efficiency of the conventional on-line type UPS as shown in Fig. 1 (b) and the proposed converter. Fig. 10 shows an efficiency characteristic with respect to the load power and Fig. 11 shows a loss analysis result. The load power is changed by adjusting a load resistor and the rated power is 3 kW. The switching frequency of the conventional on-line type converter is set to 20 kHz. Because the switching frequency of the proposed circuit is 300 Hz, the switching loss of the proposed converter is reduced by 99% compared to the conventional circuit at the stable grid condition. In contrast, conduction losses of the diode in the rectifier and the IGBT in the inverter are increased because the proposed converter employs more semiconductor devices. However the effect of reducing the switching losses is much higher than the increase of the conduction loss. As a result, the proposed circuit achieves the efficiency of 97.7% while the efficiency of the conventional converter is 94.6% at the rated power.

V. Experimental Results

A. Configulation of an experimental circuit

This chapter evaluates the operation of the proposed CVCF control using a prototype circuit in steady state. Fig. 12 shows the circuit diagram of the prototype and Table 3 shows specifications of the prototype circuit. A prototype of 3kW is constructed to confirm the fundamental operation of the proposed converter. The T-type three-level rectifier and the inverter consist of a 6in1 IGBT module (fwd), three 2in1 IGBT modules and twelve MOSFETs as bidirectional switches. The proposed circuit does not need any large electrolytic capacitors and uses only two film capacitors (2.2 μF) at DC-link. Therefore, downsizing and long lifetime are achieved by using the proposed circuit, compared to conventional on-line UPSs that use a PWM control. The prototype circuit does not include the buck chopper and the battery because this chapter confirms that the CVCF control is achieved by low speed switching frequency of six times of the grid frequency when the grid is stable. Experimental verifications of the emergency power supply and the voltage dip compensation will be reported in the future. An RL-load is used as a load in Fig. 12. The load power is changed by adjusting a load resistance (76 Ω to 13 Ω) and the rated power is 3 kW.

Then, the rated voltage of IGBTs and the bidirectional switches are calculated by following equations.

$$V_{IGBT} = \sqrt{2}V_{ac} = 200\sqrt{2} = 283[V] \tag{5}$$

$$V_{bidirectional\_switch} = \sqrt{\frac{3}{2}}V_{ac} = 200\sqrt{\frac{3}{2}} = 245[V] \tag{6}$$

where, V_{ac} is an effective value of the input line voltage. In the proposed circuit, the DC-link voltages are not smoothed and are oscillated at six times frequency by one of the grid. Accordingly, the medium phase switches of the proposed circuit require higher rated voltage, compared with a general T-type three-level converter that uses a constant DC-link voltage.

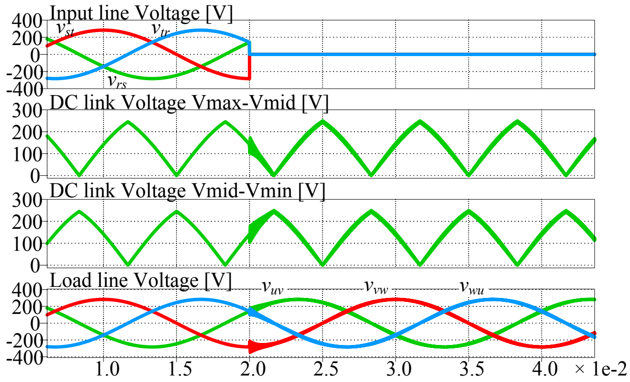


Fig. 8. Operation waveforms of the proposed circuit by simulation when the grid is fail.

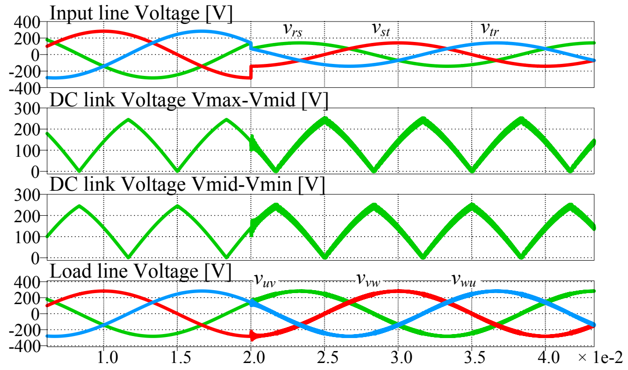


Fig. 9. Operation waveforms of the proposed circuit by simulation during the grid voltage dip.

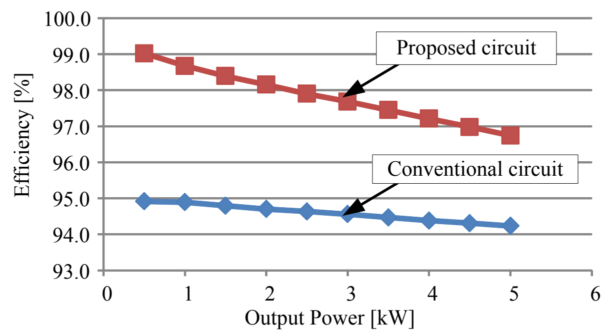


Fig. 10. Efficiency characteristic with respect to power.

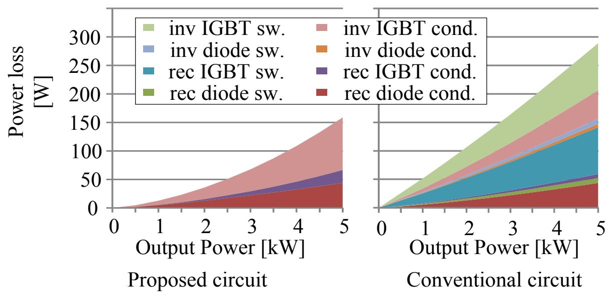


Fig. 11. Loss analysis of simulation result.

As a result, in the prototype, 600V-IGBTs and 500V-MOSFETs are selected.

A cut-off frequency f_c between the input inductances L and the DC-link capacitors C are designed not to affect the triangle waves of the DC-link voltages. A fundamental frequency of the triangle waves of the DC-link voltages f_{tri} is six times that of the grid.

$$f_{tri} = 6 f_{grid} [Hz] \tag{6}$$

Next, a cut-off frequency f_c is designed higher than f_{tri} for keep the waveform of triangle waves.

$$f_c >> f_{tri} = 6 f_{grid} \tag{7}$$

Additionally, a cut-off frequency f_c is calculated by following equations. In the proposed circuit, the switching frequency f_{sw} is the same as f_{tri} and f_{grid} is 50 Hz. Therefore, f_{sw} is equivalent to 300 Hz. Thus, parameters of L and C are set to 0.11 mH and 2.2 μF to make f_c higher than 300Hz.

$$f_c = \frac{1}{2\pi\sqrt{LC}} [Hz] = 10.2[kHz] >> 300[Hz] \tag{8}$$

B. CVCF control

Fig. 13 shows operation waveforms and switching patterns of the CVCF control which uses T-type three levels rectifier when the grid is stable. In the proposed circuit, the maximum phase and the minimum phase of the input voltage are rectified due to a diode bridge rectifier. Furthermore, the medium phase voltage is rectified by using the medium phase switches S_{rm}, S_{sm}, S_{tm}, as shown in bottom of Fig. 13. As a result, the DC-link voltage v_{max} - v_{mid} and v_{mid} - v_{min} oscillates at 300Hz as six times of the frequency of the grid. A phase difference of 30 deg. between v_{max} - v_{mid} and v_{mid} - v_{min} is confirmed because a cross point of v_{max} - v_{mid} and one of v_{mid} - v_{min} are generated at every 30deg.. In addition, the medium phase switches have no dead time because the diode rectifier prevents a short circuit.

Fig. 14 shows the inverter waveforms and u-phase switching patterns S_{up}, S_{um}, S_{un} of the T-type three-level inverter when the grid is stable. From the experimental results, due to the switching operation of the inverter at 300Hz, it is confirmed that the output voltage becomes the same as the input voltage of 200V 50Hz. In other words, the proposed converter achieves the sinusoidal load voltage without using PWM modulation. As a result, the proposed circuit can achieve downsizing and loss reduction of an EMI filter. However, the output voltage waveform has a surge voltage and the switching pulses have pulse noise periodically. The cause of the surge voltage will be found out and suppressed in the future.

C. Efficiency evaluation

In order to evaluate the proposed converter from the viewpoint of the efficiency, this section compares an efficiency of simulation results and experimental result. Fig. 14 shows the efficiency characteristics with respect to output power. The efficiency in range from 1 kW to 3 kW of the output power is

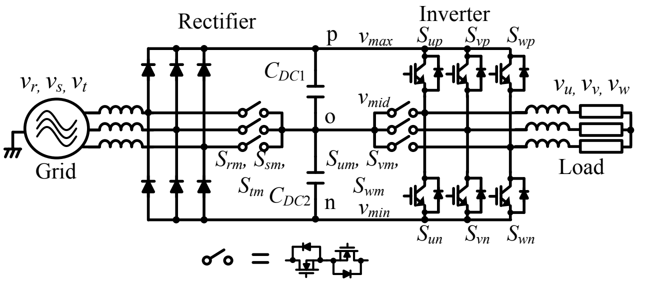


Fig. 13. Configuration of Prototype circuit.

TABLE III. SPECIFICATIONS OF PROTOTYPE CIRCUIT

Input and Output line voltage V_{ac}			200V(rms)
Rated power	3 kW	Load resistance	12.6 Ω
grid frequency	50 Hz	Load inductance	2 mH
Input inductance	0.11 mH	C_{DC1}, C_{DC2}	2.2 μF
Rectifier	6in1 IGBT module (fwd)		6MBP50NA060-01
$S_{up,vp,wp}, S_{un,vn,wn}$	2in1 IGBT module		2MBI50N-060
$S_{rm,sm,tm}, S_{um,vm,wm}$	MOSFET		2SK3522-01

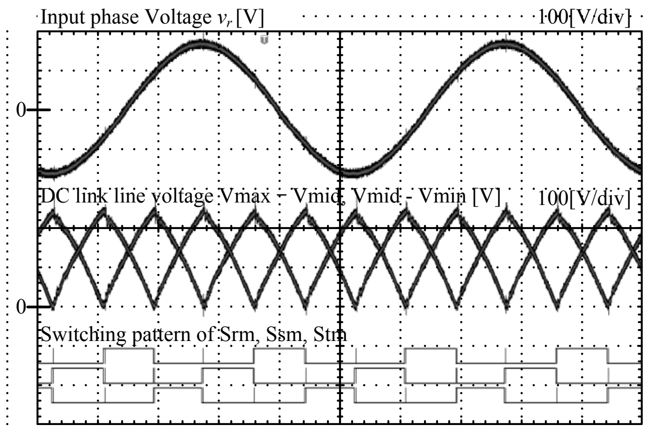


Fig. 14. Operation waveforms of the proposed circuit by experiment when the grid is not fail.

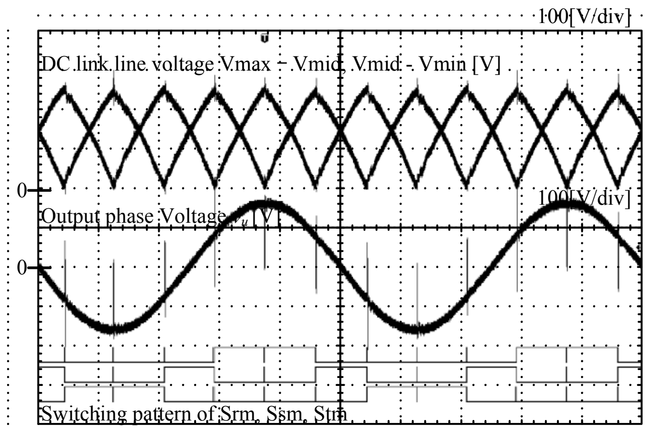


Fig. 15. Operation waveforms of the proposed circuit by experiment when the grid is not fail.

compared. From Fig.14, it is understood that the efficiency decreases with the increase of load power, and reaches 97.1% at rated power 3kW. Besides, the error between the simulation results and the experimental results is -0.6%. This is because the cupper loss and iron loss of input inductors are not considered in simulation models. Therefore, the efficiency characteristic of the prototype circuit is decreased by simulation result.

The conduction losses of the semiconductor devises and the inductors affect the efficiency mainly because the switching losses are almost reduced in the proposed circuit. Additionally, the conduction losses increase with square of current proportionally. Therefore, the efficiency characteristic decreases exponentially with increasing of load power.

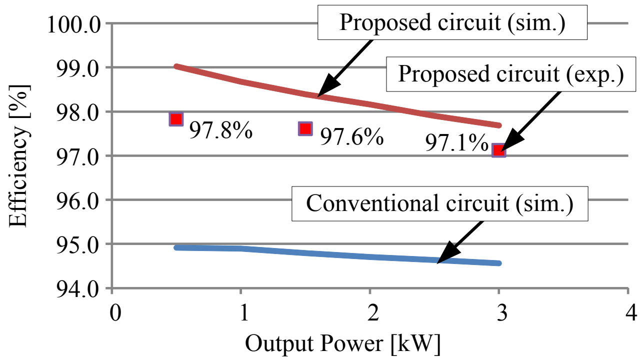


Fig. 16. Efficiency characteristic with respect to power.

VI. Conclusion

This paper proposes an AC-AC converter for an on-line UPS and confirms a fundamental operation with a simulation. As a result, the proposed converter achieves CVCF operation with the switching frequency of 300 Hz for the grid of 50 Hz. In addition, the compensations for the interruption and the grid voltage dip without the output voltage drop are confirmed. Moreover, the power loss of the proposed converter is compared to a conventional on-line UPS and the efficiency of the proposed converter is improved to 97.7%. From the results of the loss analysis, the switching loss in the proposed converter is decreased 99% comparing to that of the conventional one. From the simulation results, the increase of the efficiency to 3.3% is confirmed when the grid is stable . In addition, with the 3kW prototype, the efficiency of 97.1% was confirmed. In the future, the experimental operation in the voltage dip compensation mode and the input voltage interrupt mode will be shown in order to confirm the usefulness of the proposed converter.

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