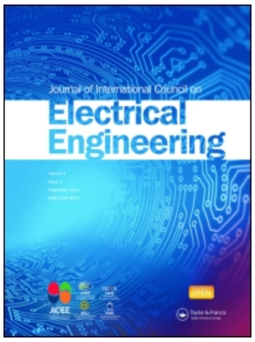

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ARTICLE

A new three-phase rectifier circuit using the partial switching strategy for a high power factor and a harmonic restraint

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ABSTRACT
This paper describes a new three-phase rectifier circuit using the partial switching strategy. A passive method to be composed of a diode rectifier circuit and an active method with the high-frequency switching were used for the circuit to convert from A.C. into D.C. mainly. However, the passive method and the active method had a problem of low power factor and low efficiency, each other. In contrast, the partial switching strategy realizes high efficiency and high power factor and low harmonics to a moderate degree. Therefore the single-phase partial switching voltage doubler rectifier circuit was applied to air conditioner. By the superior performance, most air conditioner adopts the partial switching strategy. In this paper, circuit configuration and a principle of operation and the experimental result of the three-phase partial switching rectifier circuit are reported.

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KEYWORDS
Partial switching; passive method; active method; three-phase

1. Introduction

This paper describes a new three-phase rectifier circuit using the partial switching strategy. Because most of the electric power have been sent in the form of A. C. through a transmission system, the rectifier circuit, which converts A.C. into D.C., is necessary to utilize electric power from there. Therefore, performance required for a rectifier circuit is a high power factor and high efficiency, restraint of the harmonic current. In addition, a voltage up function may be necessary. Two ways of circuits of a passive method and the active method are mainly used for the conventional rectifier circuit. The passive method is circuit composed of a diode rectifier circuit, a reactor and a capacitor [1,2]. The configuration of this circuit is simple, but a power factor is low and it does not have ability to boost voltage. In contrast, the active method is composed of a switching element, diodes, a reactor and capacitors [3,4,5]. Because current is controlled in the shape of a sinusoidal wave by high-frequency switching, the harmonic of the input current is extremely small, and power factor more than 99% is realized. But a drop of the efficiency is not avoided [6].

To solve the problems of these rectifier circuits, a single phase partial switching rectifier circuit was announced in 1999, and it was equipped in air conditioner because of the superior performance [7,8,9]. This circuit realizes a high power factor, high efficiency, and a harmonic restraint moderately, and there is ability to boost voltage. The partial switching rectifier circuit realizes various operating characteristic in a good balance. But, the case applied to a three-phase rectifier circuit does not exist. The reason is because the current flows almost as same as a phase of the line voltage, when a three-phase circuit is composed based on a conventional single phase partial switching rectifier circuit. This will be the cause that is not yet realized.

In this paper, configuration and the principle of operation of a partial switching rectifier circuit expanded to a three-phase circuit are proposed. And result of the experiment is reported for the verification of the operating characteristic.

2. Main circuit configuration

At first main circuit configuration of the single phase partial switching voltage doubler rectifier circuit which is the basic configuration of the three-phase circuit is shown. Thereafter, the three-phase partial switching rectifier circuit which is a theme of this paper is explained.

2.1 Main circuit configuration of a single phase cicuit

Figure 1 shows main circuit configuration of the single phase partial switching voltage doubler rectifier

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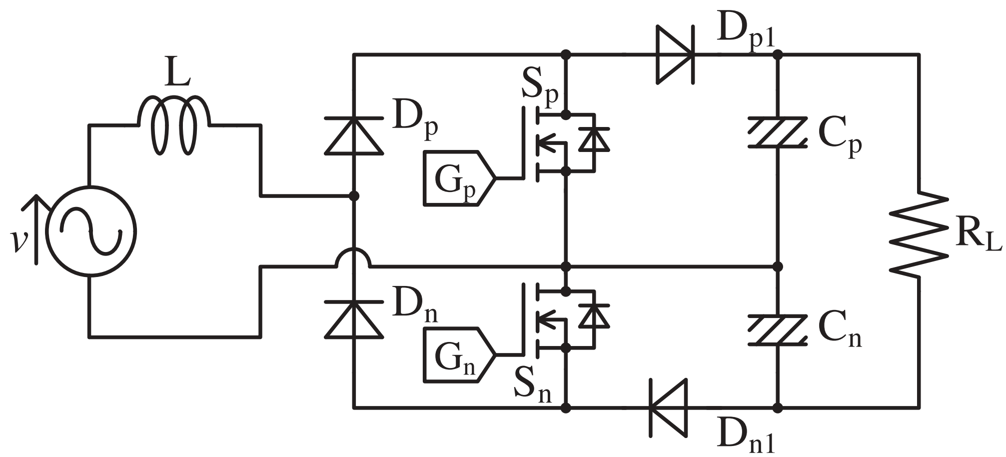


Figure 1. Main circuit configuration of a single phase partial switching voltage doubler rectifier circuit.

circuit which is the basic configuration of the three-phase partial switching rectifier circuit [10]. This circuit is composed of four diodes and two switching elements, a reactor, and two electrolytic capacitors. Two diodes of D_p, D_n and two electrolytic capacitors of C_p, C_n compose voltage doubler rectifier circuit. Two switching elements of S_p, S_n shunt a power supply through L and store inductive energy in L. The inductive energy stored in L is charged through two diodes of D_p and D_{p1} (or D_n and D_{n1}) to electrolytic capacitor C_p, C_n. This circuit converts single-phase A. C. voltage into D.C. voltage with high efficiency and low harmonics.

2.2 Main circuit configuration of three-phase circuit [11]

Figure 2 shows the main circuit configuration of the three-phase partial switching rectifier circuit. This circuit is composed of three single-phase partial switching voltage doubler rectifier circuit shown in Figure 1. This circuit is composed of switching elements and diodes, reactors and capacitors. A rectifier circuit of each phase is connected to a three-phase power supply through reactors L_U, L_V, L_W, and it is gathered in DC link. In a rectifier circuit of each phase, two switching elements are connected to DC link in series. The diodes of D_{U3}, D_{U4}, D_{V3}, D_{V4}, D_{W3}, D_{W4} are located between the switching elements of S_{U1}, S_{U2}, S_{V1}, S_{V2}, S_{W1}, S_{W2} and electrolytic capacitors of C_p, C_n, because a short-circuit of the charge of C_p, C_n are avoided.

Inductive energy is stored in L_U, L_V, L_W, when one of the switching element of S_{U1}, S_{U2}, S_{V1}, S_{V2}, S_{W1}, S_{W2} is turned on. When a switching element is turned off, inductive energy stored of L_U, L_V, L_W is charged through diodes of D_{U3}, D_{U4}, D_{V3}, D_{V4}, D_{W3}, D_{W4} to the electrolytic capacitor of C_p, C_n. Rectification and voltage up are carried out in this way.

2.3 Principle of operation

A principle of operation for the three-phase partial switching rectifier circuit to propose is explained. This circuit is composed of six switching elements. And two switching elements of the rectifier circuit of each phase are connected to DC link in series. The switching elements of upper and lower sides are not turned on at the same time. From the moment when polarity of the phase voltage turned from a negative into positive, the switching element of the upper side is turned on during set time. In addition, from the moment when polarity of the phase voltage turned from positive into a negative, the switching element of the lower side is turned on during set time. The ON time of the switching element of upper and lower sides is set to equal. There are two operation mode of this circuit for each switching element. Because six switching elements exist in this circuit, there are 12 switching modes in total. Four switching modes of the U phase are shown below.

(1) Mode 1 for the U phase (S_{U1} is turned on, $v_U \geq 0$)

From the moment when polarity of v_U switched from negative to positive, S_{U1} of the switching element of the upper side of the U phase is turned on, and line voltage v_{uv} is shunted through L_U, L_V and C_n. Figure 3(a) shows a current flow of this time. The current to flow to the U phase is shown in a solid line, and the current of other phase is shown with a dashed line.

(2) Mode 2 for the U phase (S_{U1} changed in off, $v_U \geq 0$)

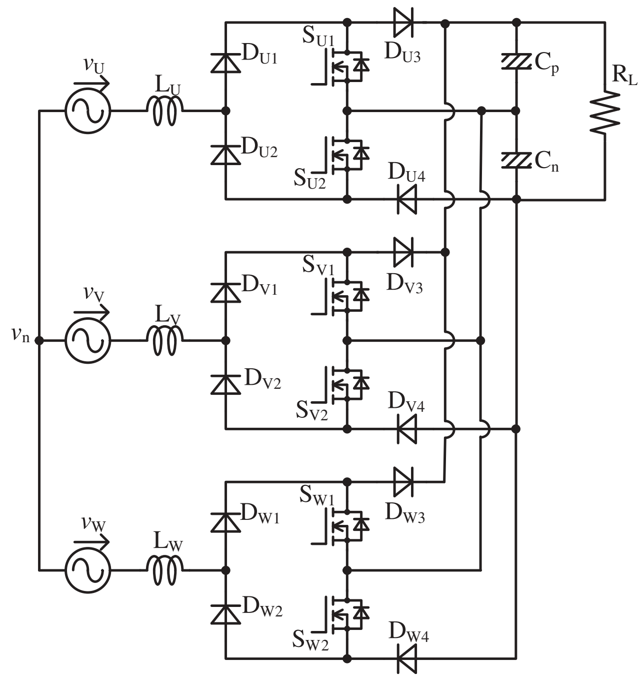


Figure 2. Main circuit configuration of the three phase partial switching rectifier circuit.

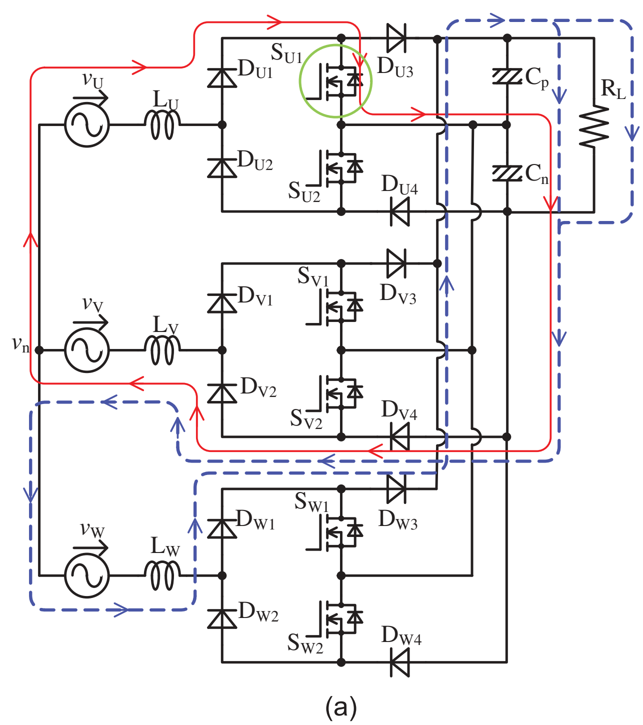
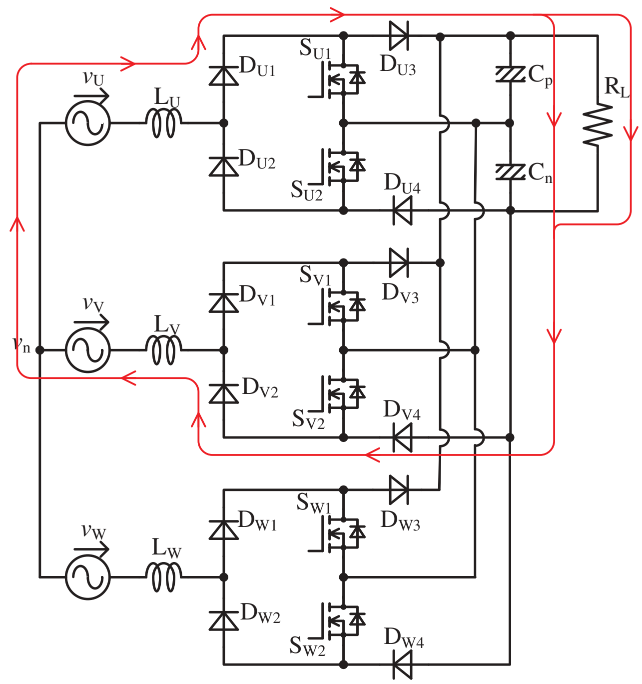
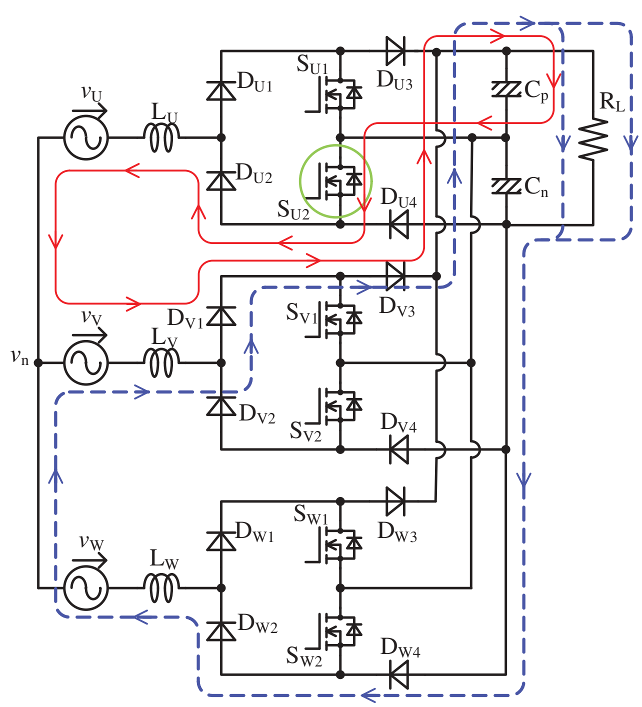


Figure 3. (a) Current flow of Mode1 (S_{U1} is turned on, $v_U \geq 0$). (b) Current flow of Mode 2 (S_{U1} changed in off, $v_U \geq 0$). (c) Current flow of Mode 3 (S_{U2} is turned on, $v_U \leq 0$). (d) Current flow of Mode 4 (S_{U2} changed in off, $v_U \leq 0$).

When set time passes, S_{U1} is turned off. Inductive energy stored in L_U and L_V is charged through D_{U3} and D_{V4} to C_p and C_n, and the DC voltage is boosted. Figure 3(b) shows a current flow of this time. Because V_{UV} becomes the maximum phase in three line voltages, the current of the W phase becomes the zero.



(b)



(c)

Figure 3. (Continued).

(3) Mode 3 for the U phase (S_{U2} is turned on, $v_U \leq 0$)

From the moment when polarity of v_U switched from positive to a negative, S_{U2} of the switching element of the lower side of the U phase is turned on, and line voltage v_{uv} is

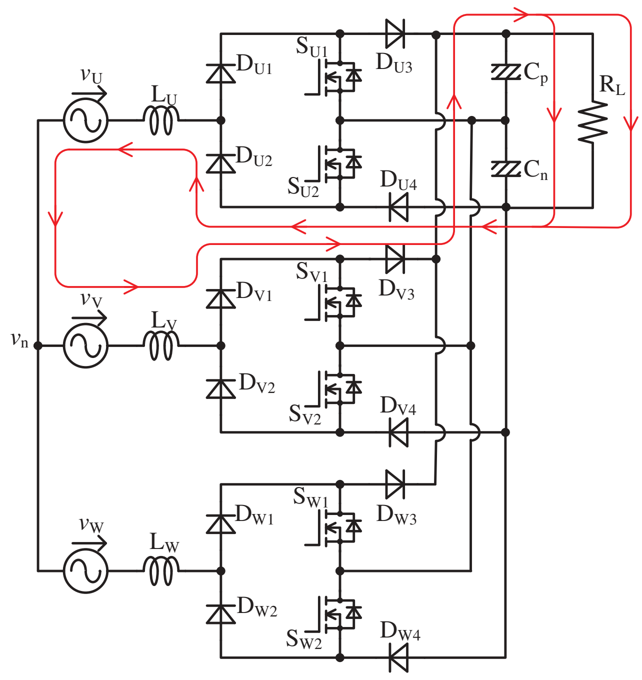


Figure 3. (Continued).

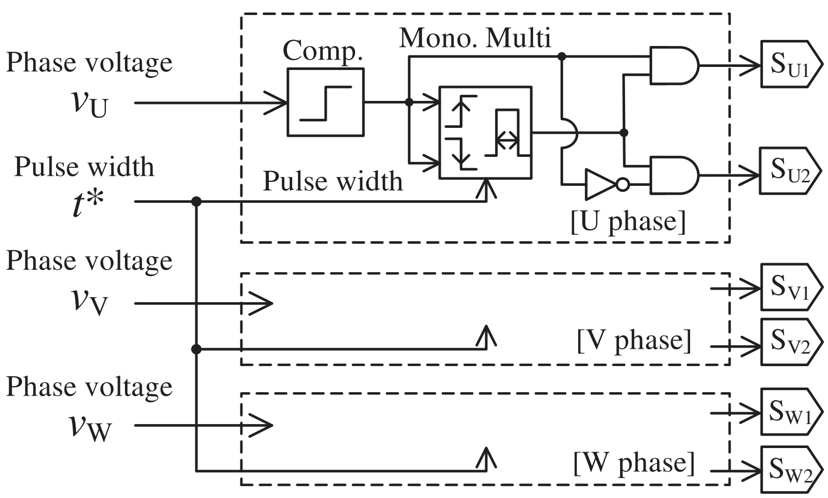


Figure 4. Control block diagram.

shunted through L_U, L_V and C_p. Figure 3(c) shows a current flow of this time. The current to flow to the U phase is shown in a solid line, and the current of other phase is shown with a dashed line.

(4) Mode 4 for the U phase (S_{U2} changed in off, $v_U \leq 0$)

When set time passes, S_{U2} is turned off. Inductive energy stored in L_U and L_V is charged through D_{U4} and D_{V3} to C_p, C_n, and the DC voltage is boosted. Figure 3(d) shows a current flow of this time. Because V_{UV} becomes the maximum phase in three line voltages, the current of the W phase becomes the zero.

2.4 The control block diagram

Figure 4 shows control block diagram [10]. This control block is composed of a zero cross comparator and monostable multivibrator. Each phase voltage is sent to a zero cross comparator, and phase voltage of the sinusoidal wave is converted into a pulse wave.

Hereby, zero cross point of the phase voltage is detected. The pulse wave is sent to a clock terminal of the monostable multivibrator. The output pulse of the monostable multivibrator is adjusted optionally by setting of the pulse width of t^*. By a logical product of pulse width and polar signal, the gate signal of the switching element is provided. In Figure 4, control block diagram only for U phase is written. V phase and the W phase are composed of the same control block, too.

3. Simulation results

Figure 5 is simulation result of the output power of 3.17kW, and Table 1 shows a condition at this time. Gate pulses are output from a moment of rise and fall of the phase voltage, and the switching element maintains ON state during pulse width of t^*. When a switching element is turned on, current rises up to comply with a rise of the voltage, and a power factor is improved. In addition, output D.C. voltage was 313V, and the power factor was 0.971.

Table 1. Condition of simulation.

Element	Symbol	Specification
Reactor	LU, LV, LW	7mH
Capacitor	Cp, Cn	1000µF
Input line voltage	^{V}UV, ^{V}VW, ^{V}WU	200Vrms
Input frequency	f	60Hz
Load resistance	RL	31Ω
Pulse width	t^*	2.0ms

4. Experimental results

The experiment was carried out to inspect an operating characteristic of proposed circuit. Figure 6 shows main circuit configuration in the experiment. Table 2 shows the specification of the elements used here. D.C. output voltage and input current, input and output power were measured, and power factor and harmonic content of the input current and power conversion efficiency were calculated. Each value was measured, when pulse width was maintained constantly and the resistance of the load was changed. The pulse width was changed after it was measured to rated power. The pulse width was gradually changed, and the

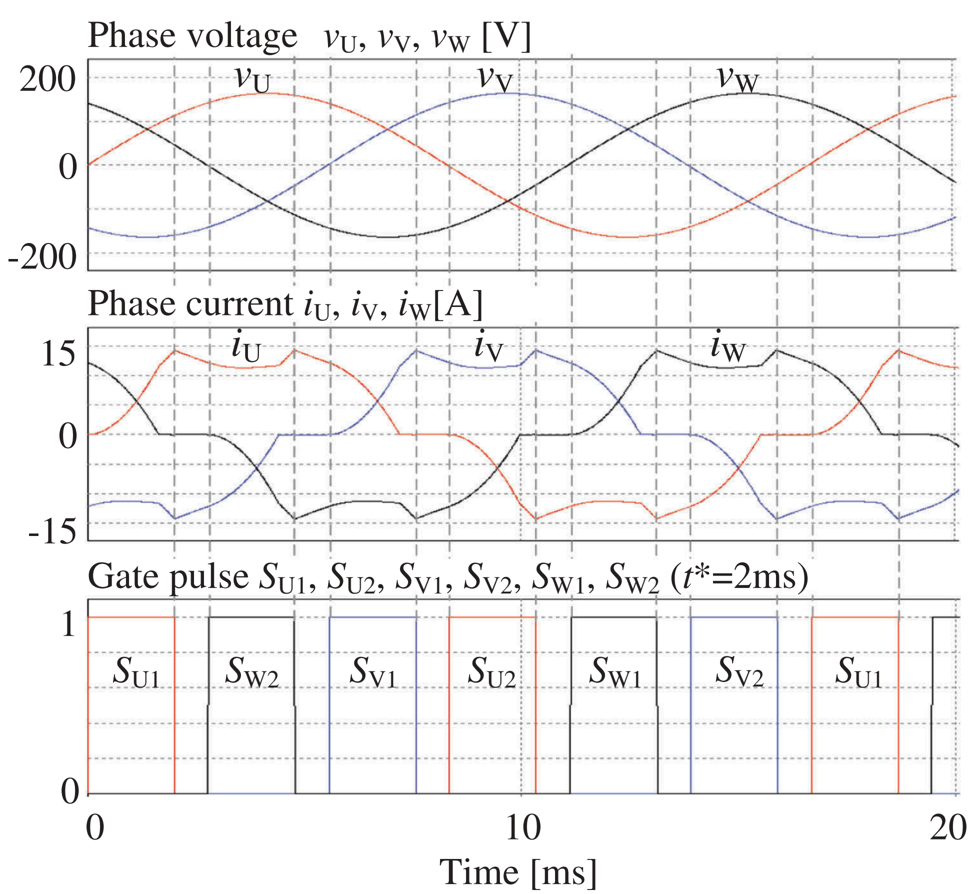


Figure 5. Simulation result (W_{out} = 3.17kW, t^* = 2ms).

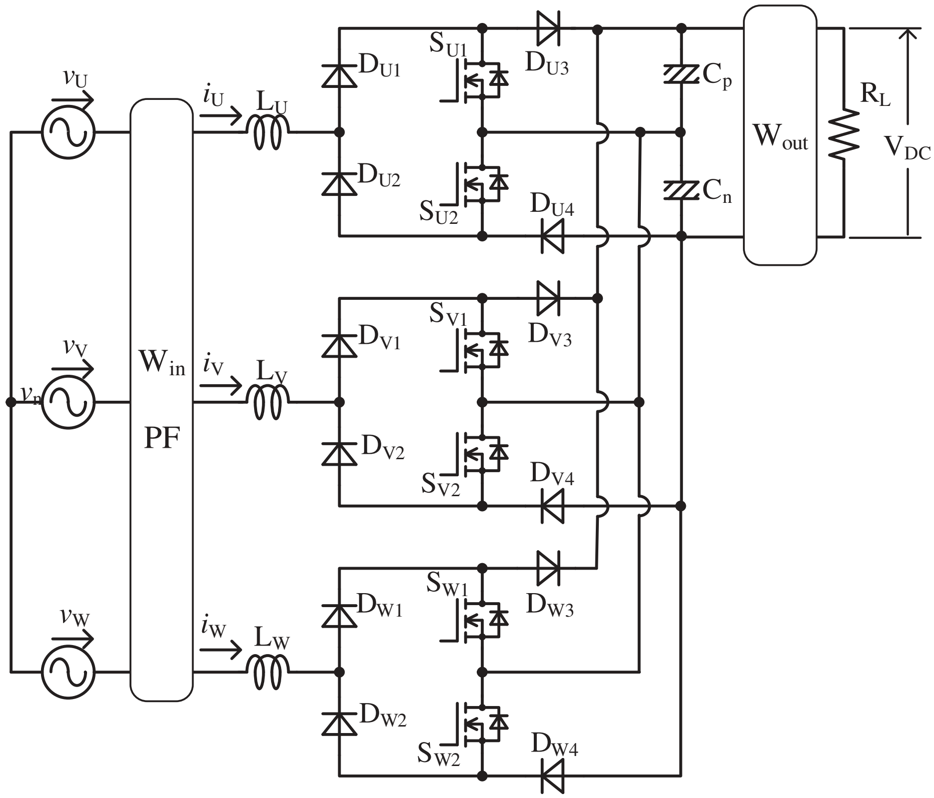


Figure 6. Main circuit configuration for Experiment.

Table 2. Specification.

Element	Symbol	Type (manufacturer)	Specification
Diode (Si)	DU1, DU2, DU3, DU4, DV1, DV2, DV3, DV4, DW1, DW2, DW3, DW4	DSEI30 (IXYS)	600V, 37A, 1.6V
MOSFET (*SiC*)	SU1, SU2, SV1, SV2, SW1, SW2	SCT3022ALDC11 (Rohm)	650V, 93A, 22mΩ
Reactor	LU, LV, LW		7mH, 20A
Capacitor	Cp, Cn		1000μF, 450V
Input line voltage	VUV, VVW, VWU		200Vrms
Input frequency	*f*		60Hz
Load resistance	RL		20Ω～270Ω
Pulse width	*t* *		1.2ms～2.4ms

measurement was repeated in the same way. In addition, the characteristic without the control of the switching element was measured, too.

Figure 7 shows input voltage and current waveforms. Three phase input current synchronizes in line voltage and begins to flow with a phase difference of 30 degrees than line voltage. The current waveform like the simulation result of Figure 5 was observed. But, the line voltage in the experiment is distorted, because several loads are connected to the same system. Output power of this time was 3.17kW, efficiency was 97.0%, and the power factor was 96.0%.

Figure 8 shows output voltage characteristics. The solid lines show the characteristics of the proposal method, and the dashed line shows a characteristic without the control. With increase of the output power, the output voltage dropped. And, with increase of the pulse width, the output voltage increased. Desired voltage and power are provided by adjusting pulse width. The characteristic without the control tended to be similar, but the output voltage was the lowest because it could not boost voltage.

Figure 9 shows power-factor characteristic. In this figure, the solid lines show the characteristics of the proposal method, and the dashed line shows a characteristic without the control. The power factor rose up with increase of the output power and dropped with increase of the pulse width. With output power more than approximately 1.8kW, the power factors became more than 0.9, and it came up to 0.98 at the maximum. In contrast, in experiment without the control, the power factor rose only approximately 0.92 at

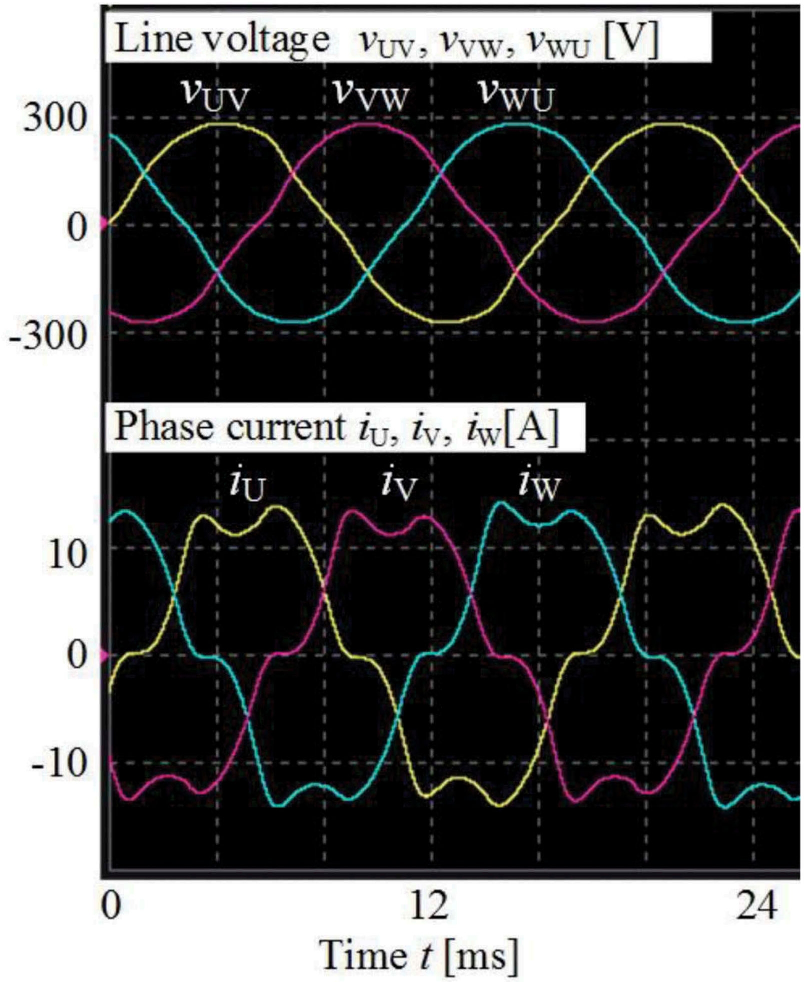


Figure 7. Waveforms of input voltage and current (W_{out} = 3.17kW, t^* = 2ms).

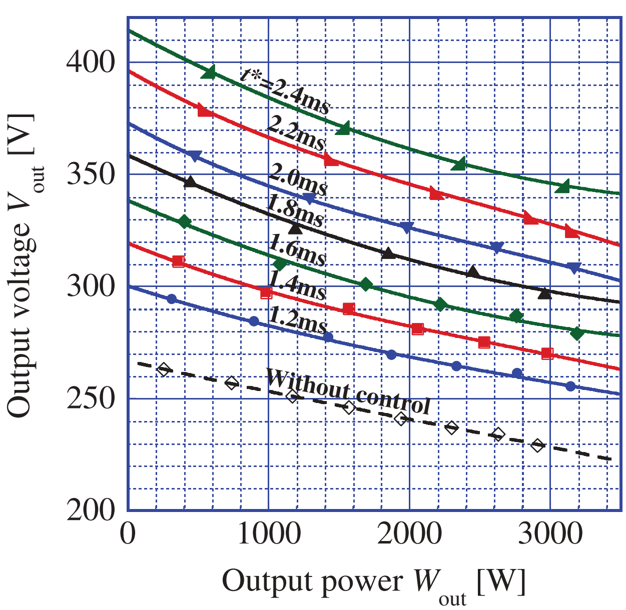


Figure 8. Output voltage characteristic.

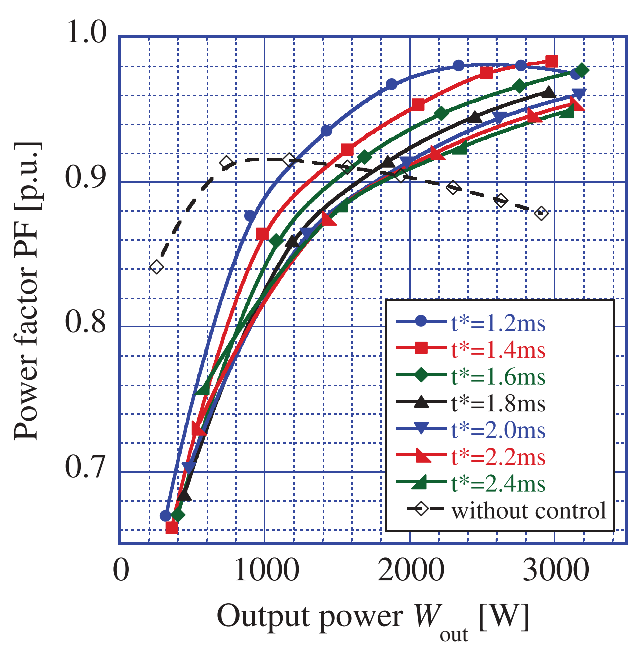


Figure 9. Power factor characteristic.

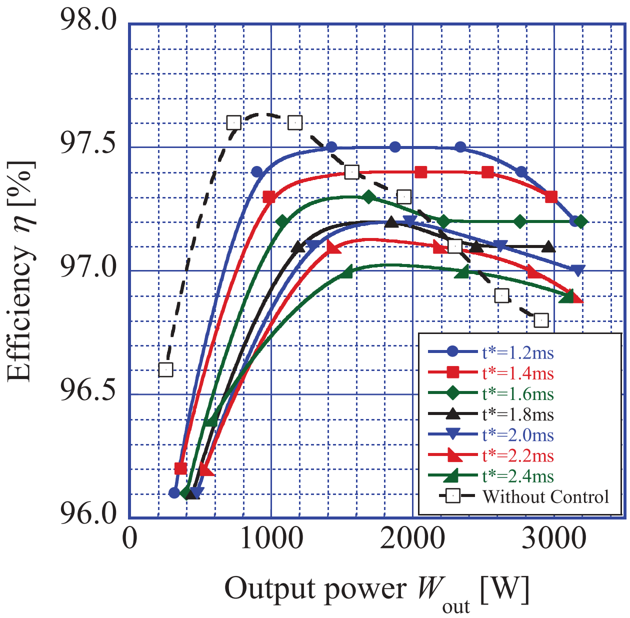


Figure 10. Efficiency characteristic.

the maximum. The power factor was higher than the proposal method in low output power, but in high output power more than 1.2kW, the proposal method exceeded it. The difference of the power factor between the circuit without the control and proposed circuit depends on a change of the harmonic current for the output power. The current waveform of the partial switching circuit becomes two tip-shaped forms at low power output. Therefore, harmonic distortion increased, and the power factor ropped.

Figure 10 shows efficiency characteristic. In this figure, the solid lines show the characteristics of the proposal method, and the dashed line shows a characteristic without the control. The efficiency dropped with increase of the pulse width. The efficiency became approximately flat in output power from 1kW to 2.5kW. 97.5% of efficiency was confirmed at the maximum. In contrast, in experiment without the control, the efficiency came up to 97.6% for output power of 1kW. In this range, this was efficiency to exceed the proposal method. However, in output power more than 1kW, the efficiency gradually dropped and lowered than the proposal method. Because output voltage and the power factor of the circuit without the control drop with increase of the output power, current more than proposal circuit flowed, and the efficiency dropped. For high output power, it was confirmed that the proposal method was high efficiency.

5. Conclusion

In this paper, the new three-phase rectifier circuit which adopted partial switching strategy was proposed. The principle of operation of this circuit was explained. The characteristics of the circuit were inspected by simulation and experiment. As a result, the followings were confirmed.

(1) This circuit has ability to boost voltage.
(2) In a heavy load condition, a power factor rises.
(3) High efficiency more than 97% is maintained in the high output.

Pulse width is selected to applications so that a desired operating characteristic is provided. Effect of the harmonic reduction of proposed circuit is inspected in future. In addition, derivation method of the pulse width to operate this circuit in the most suitable point of output voltage, power factor, efficiency, and harmonics will be investigated.

Disclosure statement

No potential conflict of interest was reported by the authors.

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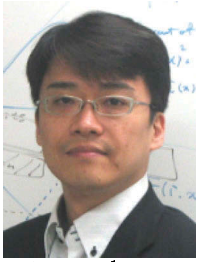

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References

[1] Mohan TM, Robbins WP. Power electronics: converters, applications, and design. New York: Wiley; 1989. p. 25–40.

[2] Takahashi I, Hori K. Single phase rectifier having small input harmonic current. IEE Jpn Trans Ind Appl. 1995;115-D(10):1215–1220.

[3] Takahashi I, Ikeshita W. Improvement of input current waveform of a single-phase recifier circuit. IEE Jpn Trans Power Energy. 1985;105-B(2):82.

[4] Martinez R, Enjeti PN. **A** high-performance single-phase rectifier. IEEE Trans Pow Elec. 1996 Mar;11(2):311–317.

[5] (Ron) Hui SY, Chung S-H, Yip S-C. A bidirectional AC–DC power converter with power factor correction. IEEE Trans Pow Elec. 2000;15(5):942–949.

[6] Morimoto M, Sumito K, Oshitani K, et al. Loss analysis of single phase sinusoidal current input converter. IEE Jpn Trans Ind Appl. 1989;109-D (6):415–422.

[7] Uesugi M, Kanazawa H, Hiruma A, et al. Single-phase twice voltage PFC converter for air conditioner. IEE Jpn Trans Ind Appl. 1999;119-D(5):592–598.

[8] Suga I, Kimata M, Uchida R. A simple switching method for a improved power factor type single phase converter. IEE Jpn Trans Ind Appl. 1996;116-D (4):420–426.

[9] Yeong J, Choi T-JK, Kim R-Y. An active partial switching method in tertiary loop for a high-efficiency predictive current-mode control PFC converter. IEEE Trans Ind Elec. 2018;65(10):7818–7828.

[10] Amei K, Kumagai A, Ohji T, et al., Characteristics of new single phase voltage doubler rectifier circuit using the partial switching strategy. *Power Electronics and Drive Systems (PEDS), 2017 IEEE 12th International Conference on*, Honolulu, USA, Dec, 2017

[11] Amei K, Kumagai A, Ohji T, et al., The partial switching method for three-phase rectifier circuit. *IEE Japan 2017 annual Meeting, 4-056*, Toyama, Japan, Mar, 2017