A Novel Three-Phase PFC Rectifier Using a Harmonic Current Injection Method

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Abstract-- **This paper proposes a novel circuit topology for a three-phase power factor correction (PFC) rectifier using a harmonics current injection method. In consideration of lower cost, the harmonics injection method is more suitable than a conventional six-arm pulse width modulation (PWM) rectifier. The harmonics injection current is simply generated by only one switching leg. As a result, the proposed circuit has the advantage of only two switches. An optimal injection current is achieved in order to obtain an input current of sinusoidal waveforms. This paper discusses the basic operation and optimal design method for the proposed circuit. In addition, the validity of the proposed circuit is confirmed by simulation and experimental results. An input current of almost sinusoidal waveform was obtained and an input current total harmonic distortion (THD) of 8.5% was obtained at a load of approximately 1 kW.**

Index Terms-- **Harmonic current injection, Three-phase diode rectifier, High power factor, Input current harmonic.**

I. INTRODUCTION

Recently, the harmonics current in a power grid can cause various problems, such as line voltage distortion, heating of power factor correction capacitors and so on. Power factor correction (PFC) rectifiers, which suppress the harmonics current, are still a very important technology. One of the most popular PFC methods for three-phase input is a full-bridge type pulse with modulation (PWM) rectifier, which consists of six arms and a boost-up reactor. The conventional PWM rectifier can obtain a sinusoidal input current without harmonics distortion. However, in regard to cost, the conventional PWM rectifier is not the best solution for the PFC. On the other hand, many three-phase PFC rectifiers that use current injection methods have been proposed [1-10]. These types of rectifiers can realize a low cost system, because they do not require many switching devices in comparison with a conventional PWM rectifier. One famous rectifier that uses the current injection method is called the Minnesota rectifier [1]. This circuit uses two boost-up choppers in part of the DC-stage. The Minnesota rectifier contains many switching devices in the main current path. Therefore, it is difficult to obtain high efficiency due to the increase in conduction losses from the switching devices in the main path.

This paper proposes a new simple three-phase PFC rectifier using a harmonic current injection method. The proposed circuit consists of two switching devices; two LC filters and a harmonic injection network. Thus, the proposed rectifier can realize lower cost than the conventional injection type PFC rectifiers. In addition, high efficiency is achieved, because the main current passes through only two diodes in addition to the diode rectifier. The injection current is controlled by the optimum method given in [3], in order to suppress the input current distortion. This paper describes the features of the proposed rectifier, and gives details of the operation and the optimum design method. Simulation and experimental results show the validity of the proposed circuit and design method.

II. CIRCUIT TOPOLOGY

A. Harmonic current injection method

Figure 1 shows the basic circuit configuration of the current injection method. The principle of this method is that the input current is composed of an input current of the diode rectifier and an injection current as shown in Fig. 1(b). When the injection current i_h, is defined by Eq. (1), the harmonic component in the input current i_a can be expressed by Eq. (2).

$$i_h = -ki_d \sin(3\omega t) \tag{1}$$
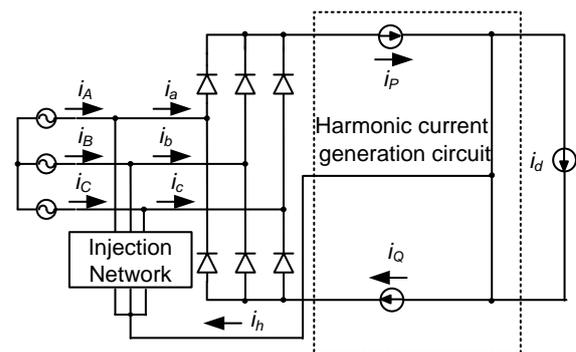
(a) Circuit configuration.
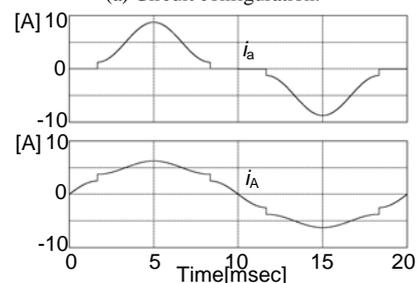
(b) Current waveform.

Fig. 1. Circuit for the harmonic current injection method.

$$i_a = \frac{\sqrt{3}}{\pi} i_d \left(2 + \frac{k}{4}\right) \sin \omega t - \frac{2}{3} k i_d \sin 3\omega t$$
$$- \frac{\sqrt{3} i_d}{\pi} \left(\frac{2}{5} - \frac{5}{8} k\right) \sin 5\omega t - \frac{\sqrt{3} i_d}{\pi} \left(\frac{2}{7} - \frac{7}{8} k\right) \sin 7\omega t \qquad (2)$$

where i_d is the dc link current, ω is the angular frequency of the input voltage, and k is the injection current gain.

Although the 1/5 and 1/7 of the 5th and 7th harmonic components are contained in the diode rectifier current i_a, those components are decreased by the injection current gain, k. The optimum injection gain k is set to 3/4 in order to obtain minimum values of the 5th and 7th harmonics components.

Figure 2 shows examples of the harmonic current injection network. The harmonics current is equally injected through these circuits to AC side. The power capacity of the injection network is not so large, since each phase current becomes about 1/4 of the DC link current. It should be noted that if a system has an isolation transformer in the input side, the neutral point of the isolation transformer can be used instead of the injection network.

B. Conventional circuit

Figure 3 shows one of the conventional three-phase PFC rectifiers using the harmonic current injection method, which is called a Minnesota rectifier. This rectifier consists of a three-phase diode bridge rectifier, two series-connection boost converters, and the harmonic current injection network. In this circuit, the injection current i_h is generated by controlling i_P and i_Q. The injection current is obtained using Eq. (3).

$$i_h = i_p + i_Q \qquad (3)$$

The features of this circuit are as follows: the efficiency decreases because the main current path contains two diodes in addition to the diode bridge part; the output voltage v_d is constrained in Eq. (4), because the boost converter is used based on the neutral point voltage of the power supply.

$$v_d \geq 2V_m \qquad (4)$$

where, V_m represents the peak value of the input voltage.

C. Proposed circuit

Figure 4 shows the main circuit of the proposed three-phase PFC rectifier, which uses a single leg for the harmonic current injection circuit. This rectifier requires a three-phase diode bridge, a switching leg that consists of S_1 and S_2, a filter reactor L_f, filter capacitor C_f, a DC reactor L_d, and the harmonic current injection network. The harmonic component of the switching frequency in the DC current is reduced by the LC-filter.

In this circuit, the injection current i_h is directly controlled by S_1 and S_2. The injection current flows depending on the voltage difference between points P or N and point M. That is, when S_1 is turned on, the injection current can be obtained by Eq. (5), if the current of the capacitor C_f is neglected.

(a) Tuned LC filter.   (b) Star/delta transformer.   (c) Zigzag transformer.
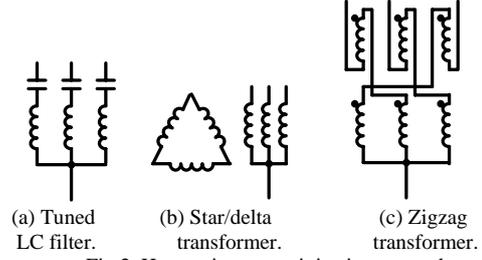
Fig.2. Harmonic current injection network.
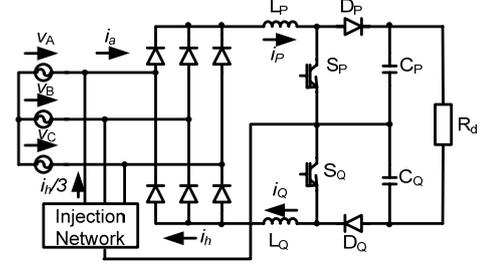
Fig. 3. Main circuit of a Minnesota rectifier.
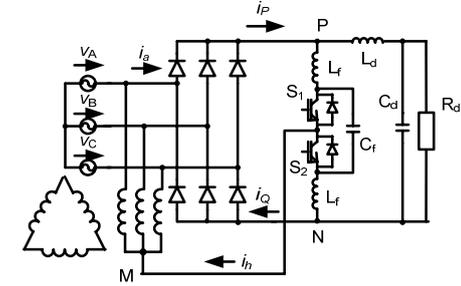
Fig.4. Main circuit of the proposed three-phase harmonic current injection method PFC rectifier.

$$\frac{di_h}{dt} = \frac{1}{L_f + L_{inj}} (V_P - V_M) > 0 \qquad (5)$$

Similarly, when S_2 is turned on, the injection current becomes that given by Eq. (6).

$$\frac{di_h}{dt} = \frac{1}{L_f + L_{inj}} (V_N - V_M) < 0 \qquad (6)$$

where L_{inj} is the leakage inductance of the current injection network.

Hence, it is possible to control the injection current, since the increase and decrease of the current can be controlled by S_1 and S_2, as shown in Eqs. (5) and (6). It is noted that the output voltage v_d of the proposed circuit becomes the same as a normal three-phase diode bridge.

The proposed rectifier has following advantages over the conventional rectifier (Minnesota rectifier):

(a) High efficiency is obtained because the main current passes through only two diodes, which are used as a diode bridge.

(b) The filter reactor realizes a reduction in size, due to the following AC current. In the conventional circuit, L_P, L_Q requires a DC reactor. The volume of the AC reactor is smaller than the DC reactor.

III. CONTROL STRATEGY

Figure 5 shows the relation between the input current command and the optimum injection current command i_h. As discussed in chapter II, the injection current can improve the input current waveform to a sinusoidal current. In this chapter, we apply an optimum harmonic

current to the proposed circuit. While the i_a is blocked by the diode rectifier, the injection current i_h only appears in the input current. Hence, the waveform of i_h has to fit to a part of the sinusoidal waveform if we want to achieve a sinusoidal input current. As a result, the optimum harmonic current is obtained by the middle signal in the three-phase current command, as show in Ref. [4]. Therefore, the optimum harmonic current command i_h is obtained by Eq. (7).

$$i_h = 3[i_A, i_B, i_C]_{max} + 3[i_A, i_B, i_C]_{min} \qquad (7)$$

where $[i_A, i_B, i_C]_{max}$ represents the maximum input current command, and $[i_A, i_B, i_C]_{min}$ represent the minimum input current commands. The input current commands $[i_A, i_B, i_C]$ are unity sinusoidal waveforms, which are synchronized with the power supply voltage.

Figure 6 shows the control block diagram of the proposed circuit. A hysteresis current controller is applied in order to suppress the switching ripple of the injection current. In this case, the ripple current can be controlled by the bandwidth of the hysteresis current controller. The input voltages v_A, v_B, v_C and DC inductance current i_{Ld} are detected in order to calculate the input current commands i_A^*, i_B^*, i_C^*. It should be noted that an inexpensive detection circuit, such as a shunt resistor, can be used since the DC link current detection does not require quick response or high accuracy. The optimum harmonic current command i_h^* is calculated from i_A^*, i_B^*, i_C^* and Eq. (7).

IV. CIRCUIT DESIGN

A. Design of the DC link reactor

In the proposed circuit, i_P and i_Q, shown in Fig. 4, depend on the difference between the DC link reactor current i_{Ld} and i_h, although i_h is directly controlled by the hysteresis current regulator. Therefore, to suppress the distortion of the input current, the DC link reactor current i_{Ld} must be maintained as constant. However, the i_{Ld} ripple is caused by the diode bridge output voltage v_{PM}, and v_{PM} is obtained using Eq. (8).

$$v_{PM} = \frac{3\sqrt{3}}{\pi}V_m + \frac{6\sqrt{3}}{35\pi}V_m \cos 6\omega t - \frac{6\sqrt{3}}{143\pi}V_m \cos 12\omega t + \cdots \quad (8)$$

where, V_m is the peak of the input voltage.

From Eq. (8), the AC component of the DC link reactor current i_{LdAC} is obtained by Eq. (9)

$$i_{LdAC} = -\frac{6\sqrt{3}}{35\pi}\frac{V_m}{6\omega L_d}\sin 6\omega t + \frac{6\sqrt{3}}{143\pi}\frac{V_m}{12\omega L_d}\sin 12\omega t \cdots \quad (9)$$

It should be mentioned that in Eq. (8) the 6th harmonic current is dominant in i_{LdAC}. Therefore, only the 6th harmonic current is considered in the following discussions. The ripple rate of the DC current caused by the 6th harmonic current is equal to the ripple rate of the output power under constant DC voltage. That is, the total harmonics distortion (THD) of the DC side THD_{DC} can be calculated by Eq. (10).

$$THD_{DC} = \frac{I_{m6}}{I_d} \times 100 = \frac{3VI_6}{3VI} \times 100 = \frac{I_5 + I_7}{I} \times 100 \qquad (10)$$
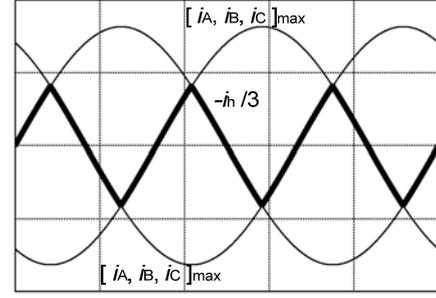
Fig.5. Input current reference and i_h^*.
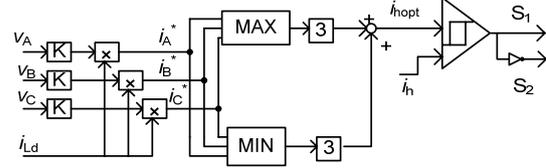
Fig. 6. Control block diagram for the proposed circuit.
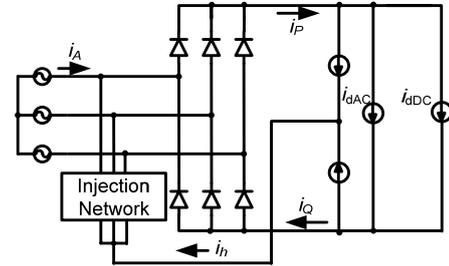
Fig.7. Simulation circuit for the ripple analysis.

where, I_{m6} is the peak value of the 6th harmonic current, I is the fundamental frequency component of the input current, I_5, I_6 and I_7 are the 5th, 6th and 7th harmonic components for the input current, I_d is the value of the DC current, and V is the input voltage.

The 5th and 7th harmonic components in the input current appear when the DC current contains the 6th harmonic component. Then, the input current THD (THD_{AC}) is calculated by Eq. (11).

$$THD_{AC} = \frac{\sqrt{I_5^2 + I_7^2}}{I} \times 100 \qquad (11)$$

Therefore Eq. (12), which expresses the relationship between THD_{AC} and THD_{DC} is derived from Eqs. (10) and (11).

$$THD_{AC} = \frac{\sqrt{I_5^2 + I_7^2}}{I_5 + I_7} THD_{DC} \qquad (12)$$

Figure 7 shows the simulation circuit used to confirm the propriety of Eq. (12). Ideal current sources are used instead of the switching leg and the DC reactor. The current source i_{dAC} assumes the ripple of the 6th harmonic in the dc current. The relationship of THD_{DC} and THD_{AC} is investigated by changing the magnitude of the current source i_{dAC}.

Figure 8 shows the comparison of the simulation results and calculated results from Eq. (12). The simulated results agree well with the calculated results using Eq. (12). In this case, the relation of Eq. (13) is obtained, because the magnitude of I_5 is almost the same as the magnitude of I_7.

$$THD_{AC} = \frac{THD_{DC}}{\sqrt{2}} \qquad (13)$$

The propriety of equation (13) was identified as simulation result by agreement of equation (13).

Figure 9 shows relation between the value of the DC link reactor and the THD of the input current, and is derived from Eqs. (9) and (13). The value of the dc reactor is expressed by the percentage unit based on the power supply voltage, frequency and converter power capacity. It is suggested from Fig. 9, that the DC reactor of 10% is required in order to obtain an input current THD of less than 10%.

B. Design of the LC-filter

The proposed circuit reduces the harmonic component of the switching frequency using a LC-filter. The filter reactor L_f and capacitor C_f are connected in parallel with the output side of the diode bridge. There are two factors that influence the input current in the LC-filter design.

1) Phase shift of harmonic current

Figure 10 illustrates the influence of the LC filter using a simulation waveform of the input current when the phase between the injection current i_h and the DC current i_P or i_Q is delayed by the LC filter. The phase shift from the LC filter causes the distortion of the input current, because the current i_a can not pass through the diode rectifier, except for only 60 degrees in the half period of the power supply. Figure 10(b) shows the relationship between the input current THD and the phase shift by the simulation. As a result, the input current THD increases in proportion to the phase shift.

The input current THD can be reduced by increasing the impedance of the LC-filter, because the phase shift is caused by the LC filter current. The impedance of the LC-filter(Z_f) is expressed by Eq. (14)

$$Z_f = 2j\omega L_f + \frac{1}{j\omega C_f} = -j\frac{1 - 2\omega^2 L_f C_f}{\omega C_f} \qquad (14)$$

Figure 11 shows the relation between the impedance ratio of Z_f to the rated impedance Z_0, which is based on the rated voltage, frequency and power capacity, and the input current THD. It is noted that the decrease of the input current THD depends on the increase in Z_f

2) Harmonic component of the switching frequency

If the cutoff frequency (f_c) of the LC-filter is close to the switching frequency (f_s), the harmonic component of the f_s remains. Therefore, the f_c has to be designed at a sufficiently low frequency for the f_s. However, too low a f_c causes a phase shift, as discussed previously.

On the other hand, the switching frequency f_s depends on the hysteresis width I_{his}, the impedance of the current injection network L_{inj}, and the filter reactor L_f, as shown in Eq. (15), because the PWM pattern is used by the hysteresis current regulator.

$$f_s = \frac{1}{2I_{his}} \frac{[v_A, v_B, v_C]_{max}}{L_f + L_{inj}} \qquad (15)$$

where $[v_A, v_B, v_C]_{max}$ means the maximum input voltage. L_{inj} and I_{his} are designed from equation (15).
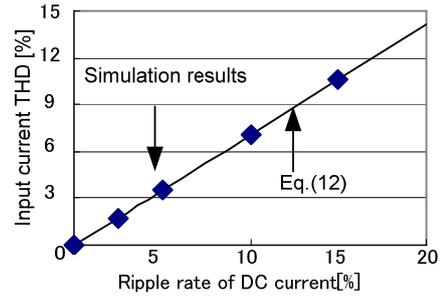
Fig. 8. Distortion in the input current depending on the ripple rate of i_{Ld}.
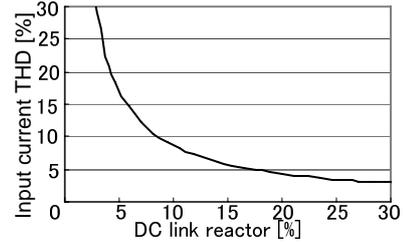
Fig.9. Relation between the DC link reactor and the input current THD.
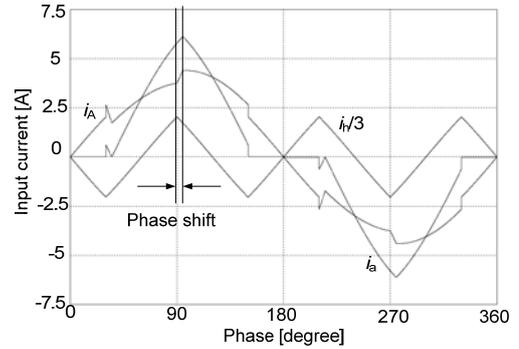
(a) Simulation waveform for input current.
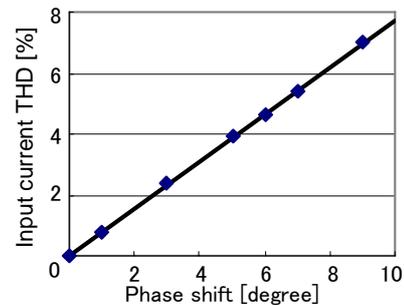
(b) Input current THD dependence on the phase shift.
Fig.10. The influence of the phase shift of the harmonic current on the input current THD.
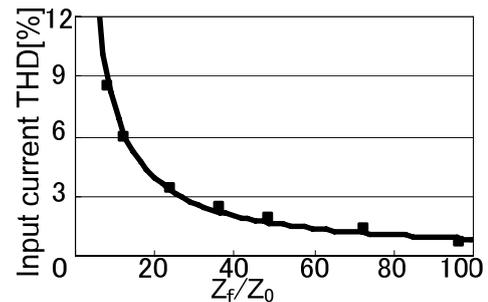
Fig.11. Relation between Z_f/Z_0 and the input current THD.

Figure 12 shows the relationships amongst the input current THD, the LC-filter impedance and the cutoff frequency when the DC reactor current is maintained as constant. In the f_c/f_s region from 20% to 90%, the increase in the input current THD depends on the increase of the cutoff frequency, because the harmonic component of the switching frequency dominates the distortion of the input current. However, in the f_c/f_s region around 10%, the input current THD is increased from the influence of the phase shift. Similarly, in case of the Z_f/Z_0 region under 50, the LC-filter current causes distortion of the input current.

C. Example of the circuit design

The circuit parameters can be designed from Fig. 9 and 12 in order to realize the desired input current THD. For example, an input current THD of less than 10% can be designed for the proposed circuit. Firstly, the cutoff frequency is selected as 20% of the switching frequency, using Fig. 12. Then the impedance of L_f is obtained at 2.4%, and the admittance of C_f is simultaneously determined as 5.5%. As a result, the design point in Fig. 12 is selected at an input current THD of approximately 8%. The 6th harmonic current is dominant in the THD that is caused by the DC link reactor (THD_{DCL}), and the resonant frequency of the LC filter dominates the harmonics components of the input current THD. Therefore, the allowance for the DC reactor current THD_{DCL} is obtained by Eq. (16), using THD_f which dominates the resonant frequency. In this example, the DC reactor current THD has to suppress less than 6%. Lastly, the value of the DC reactor is determined as 14% from Fig. 9.

$$THD_{DCL} = \sqrt{THD^2 - THD_f{}^2} = \sqrt{10^2 - 8^2} = 6[\%] \qquad (16)$$

V. SIMULATION AND EXPERIMENTAL RESULTS

Table 1 shows the experimental and simulation conditions that were derived in chapter III-C. The simulation is used in order to check the fundamental operation and the validity of the circuit parameters. The switching frequency depends on the hysteresis bandwidth and the reactor as already explained. The switching frequency is designed to be approximately 10 kHz. It is noted that the DC reactor seems to have a large value. However, the DC reactor can be small for use with an electric inductor [11] or a current type load.

Figure 13 shows the simulation results of the proposed circuit using the parameters of Table 1. A THD of 7.2% and a unity power factor are obtained. In addition, a constant output voltage on the DC side is also obtained. It is noted that the one of the causes of this is the DC link current ripple, which occurs with the current distortion around the peak of the input current.

Figure 14 shows the experimental results of the proposed circuit with a resistive load under the same condition as shown in Fig. 13. We can confirm that the sinusoidal input current and unity power factor are
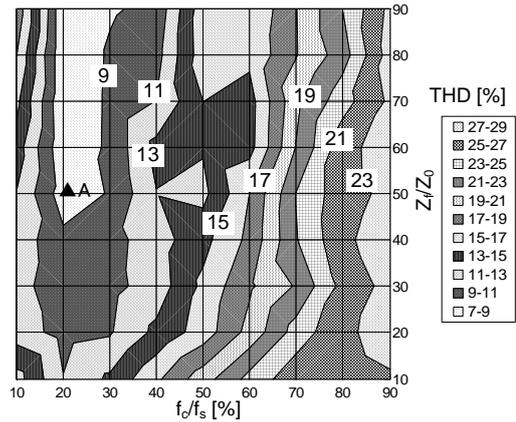
Fig.12. Relation between the filter and the input current THD.

TABLE 1 SIMULATION CONDITIONS.

Item	Value	Item	Value
Rated line voltage	200 V	Rated output power	1 kW
f_c/f_s	20 %	Cf(admitance)	5.50 %
Input frequency	50 Hz	Lf	2.40 %
DC capacitor	2200 uF	Ld	14 %
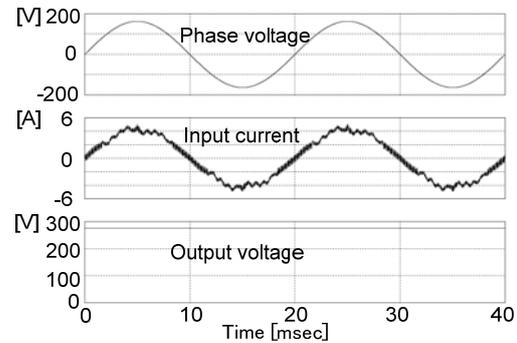
Fig.13. Simulation results for the proposed circuit.
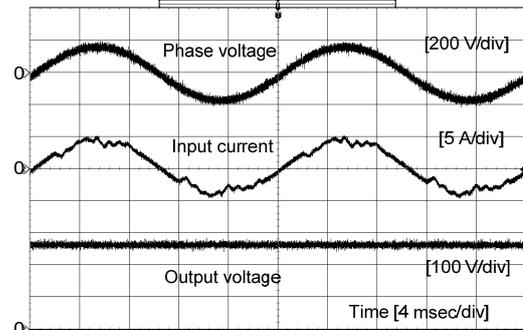
Fig.14. Experimental results for the proposed circuit.

obtained are the same as the simulated results. Furthermore, it is confirmed that the output voltage is also maintained constant. A THD of 8.5 %, which is almost the same as the simulated results, was obtained. We consider that the causes of the difference between the simulated and experimental results are the accuracy of the circuit parameters and the imbalance in the impedance of the power supply.

Figure 15 shows the THD characteristics of the input current against the output power. The input current THD of the proposed circuit increases according to the decrease in the output power, since the harmonics current is constant, although the fundamental current becomes

small in the light load region.

Figure 16 shows the efficiency and input power factor for the proposed converter. A maximum efficiency of 96.2 % is obtained. In addition, an input power factor of over 99% is obtained for a load over 50%. In the light load region, the power factor decreases, because the THD of the input current increases as shown in Fig. 15.

Figure 17 shows a comparison of the converter loss between the proposed circuit and a conventional circuit based on the experimental results. The conventional circuit was made under the conditions given in Table 2. A maximum efficiency of 95.4% was obtained for the conventional circuit at the rated load. Therefore, the proposed circuit improves the efficiency by 0.8% compared to the conventional circuit. The converter loss can be reduced by approximately 20% at the rated load using the proposed circuit. It is noted that the difference in the loss between the proposed and conventional circuit increases according to a heavy load. The reason for this is that the condition loss of the boost up diode in the conventional circuit dominates the total loss.
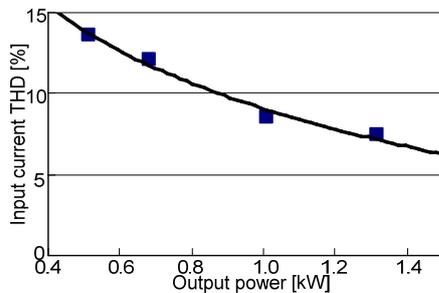
Fig.15. Characteristics of the input current THD.

TABLE 2 EXPERIMENTAL CONDITIONS FOR CONVENTIONAL CIRCUIT.

Item	Value	Item	Value
Rated Line voltage	200 V	Rated output power	1 kW
Input frequency	50 Hz	L	2.40 %
DC capacitor	2200 uF		
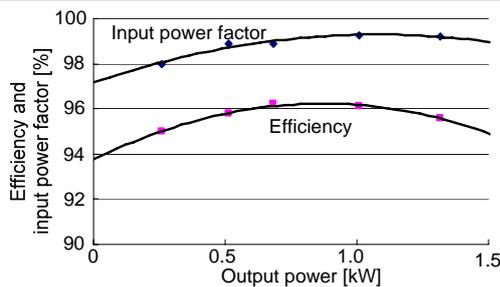
Fig.16. Efficiency and input power factor for the proposed circuit.
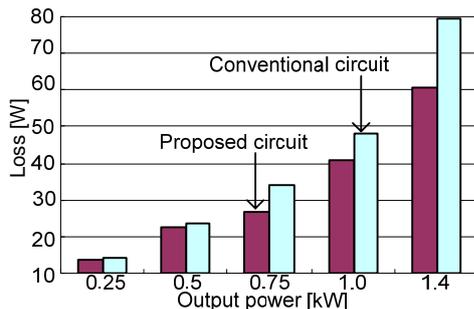
Fig.17. Comparison of the converter loss.

VI. CONCLUSIONS

This paper proposed a novel three-phase current injection method PFC rectifier. In addition, the basic operation and optimum design were discussed. The proposed circuit has the following features;

-the additional circuit components to the normal diode rectifier are one leg, a LC filter and injection circuit;

- the input current THD is 8.5% at the rated load (1 kW);

-the proposed circuit can reduce the converter loss by 20% that for the conventional Minnesota rectifier.

The validity of the proposed circuit and the optimum design method are confirmed with simulated and experimental results. In future study, the volume of the DC reactor will be reduced by optimum control, depending on the DC current ripple.

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