Experimental Verification for a Matrix Converter with a V-connection AC Chopper

Kazuhiro Koiwa and Jun-ichi Itoh
Nagaoka University of Technology
1603-1 Kamitomioka-cho
Nagaoka city Niigata, Japan
Tel. / Fax: +81/ (258) – 47.9533.
E-Mail: itoh@vos.nagaokaut.ac.jp
URL: http://itohserver01.nagaokaut.ac.jp/itohlab/index.html

Keywords

«Matrix converter», «Converter control», «current/voltage control»

Abstract

This paper proposes a circuit topology for a matrix converter with a boost up function in the input side. The proposed circuit uses a V-connection AC chopper to achieve the boost-up function. The matrix converter and the V-connection AC chopper are independently controlled, where a virtual indirect control method is applied to the matrix converter, and the control of the V-connection AC chopper is an open-loop control with a damping. One problem of this system is the resonance happens between the input reactor and the filter capacitor. In order to suppress the resonance, the damping control is implemented in the AC chopper. In this paper, the operation of the proposed circuit along with the loss analysis is discussed in details. For the simulation and experiment results, the proposed circuit is confirmed obtaining the maximum efficiency of 95.1 %, which is higher efficiency than that of a conventional back-to-back converter.

I. Introduction

A matrix converter (MC) which can convert an AC power supply voltage directly into an AC output voltage of variable amplitude and frequency without the large energy storages, such as electrolytic capacitors, have been actively studied recently [1-4]. The following advantages are found as compared with a back-to-back converter, which consist of a PWM rectifier and a PWM inverter; (i) light-weight and long-life due to no large passive components in the main circuit (ii) high efficiency because of less switching devices in the current path. The MC is expected to apply in the renewable energy field such as hybrid electric vehicle systems, the wind power generator systems and others.

However, one disadvantage of the MC is the voltage transfer ratio, which defines as the ratio between the output voltage and the input voltage, is being constrained to 0.866. Consequently, the output current of the MC is higher than that of the back-to-back (BTB) type converter, under the same output power. Even the motor can drive at rated frequency as the field-weakening control is applied. However, the output current is increased and the efficiency of the system is reduced. Further, the motor loss increases due to the high input motor current. Besides, the restricted voltage transfer ratio also limits the applications of the MCs.

There are many discussion topics on improving the voltage transfer ratio of the MCs. One of the easy solutions is to connect a transformer between the power supply and the MC. However, the commercial frequency transformer applied in the power grid frequency is bulky.

On the other hand, a Matrix-Reactance Frequency Converter (MRFC), which consists of a MC and an AC chopper, has been studied in [2]. Reference [2] shows that, the amplitude of the output voltage can control to extend which is higher than that of the input voltage. However the MRFC requires many components due to the insertion of the boost up reactor and capacitor. In addition, the control becomes complicated due to the regular synchronizing between the MC and the chopper is required.

In the Ref. [4], the MC has been proposed to operate in an over modulation range. The voltage transfer ratio is successfully improved to 0.94. However, the input current and the output voltage contain large harmonic components. Additionally, the output voltage amplitude by the over modulation method cannot get over the amplitude of the input voltage. In other word, the MC cannot apply for the higher voltage application than the input voltage. Therefore, in considering of applying the MC in the near future of power electronics field, the boost-up functionality is important.

This paper evaluates a matrix converter circuit topology which connects a V-connection AC chopper at the input side of the MC that comes with a boost up functionality. The additional component of this circuit is consists of the bidirectional switches only because the reactors in the input filter are being used as boost reactors in this method. One of the features in this system is that an automatic voltage controller (AVR) for the chopper is not required. As a result, the capacitor in the boost-stage is smaller than that of the DC capacitor in the BTB system. Moreover, the origin advantages of the MC remain in the proposed circuit because the V-connection AC chopper does not work when the output voltage is lower than the limitation of the voltage transfer ratio for the MC.

In this paper, the proposed circuit is demonstrated by using a 1.4 kW prototype. The fundamental operation and the validity of the proposed method are confirmed by the experimental results, where the maximum efficiency of 95.1 % and the input power factor of 0.996 are obtained respectively.

II. Circuit topology

2.1 BTB system

Figure 1 shows the circuit diagram of a back-to-back (BTB) converter, which consists of a PWM rectifier and an inverter. This system requires a large electrolytic capacitor in the DC link part to reduce the ripple voltage formed by the rectifier. The PWM rectifier requires an automatic current regulator (ACR) to control the input current. Besides that, an automatic voltage regulator (AVR) for the DC link voltage is also required to obtain the input current command. Then, the minimum capacitor value is constrained by the control response of the DC link voltage and the input current according to the AVR and ACR.

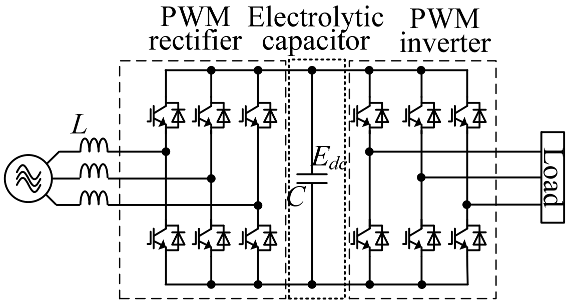


Fig. 1. Circuit configuration of the BTB system.

2.2 Proposed circuit

Figure 2 shows the proposed circuit diagram. The proposed circuit connects a V-connection AC chopper in the input side of the MC. The additional components are based on four reverse blocking IGBTs (RB-IGBT) that is mainly constructed by silicon and diodes. The relationships between the input voltage v_{in} and the output voltage v_{out} is expressed by

$$v_{out} = \beta_{chop} \cdot \lambda_{mc} \cdot v_{in} \quad (1)$$

where, λ_{mc} is the modulation index of the MC, β_{chop} is the boost-up ratio of the chopper and v_{in} is the input voltage. The proposed circuit does not require a voltage control for the input capacitor since both the input side and the output side of the V-connection chopper are AC voltage; i.e. the voltage control of the V-connection chopper uses an open loop control. Therefore, the capacitor value does not dominant by the voltage control response and the current response for the input side. As a result, the V-connection AC chopper and its components do not dominate the size and the weight in comparison to the origin structure of a MC.

The maximum output voltage of the proposed circuit is decided by the duty ratio of the V-connection chopper. It should be noted that the switches in the V-connection chopper do not operate when the voltage transfer ratio is lower than 0.866 of the input voltage. That is, at the range of low output voltage, the proposed circuit is able to obtain high efficiency similarly to the original MC.

Besides, since the MC uses bi-directional switches, are required to apply with commutation pattern to prevent the source and load from open circuit and short circuit. In this paper, the 4-step commutation method is applied in the proposed circuit [8]. And also, the voltage of the filter capacitors is used in this commutation.

Figure 3 shows the control block diagram of the proposed circuit. The pulse pattern of the MC is generated by the virtual indirect control method [4]. The MC and the V-connection chopper can be controlled independently. The proposed stability control is implemented on the d-q frame of the AC chopper control. It should be noted that the proposed control does not require a high speed feedback regulator. It means that the filter capacitor and the filter reactor are not dominated by the control response of the input current and the capacitor voltage.

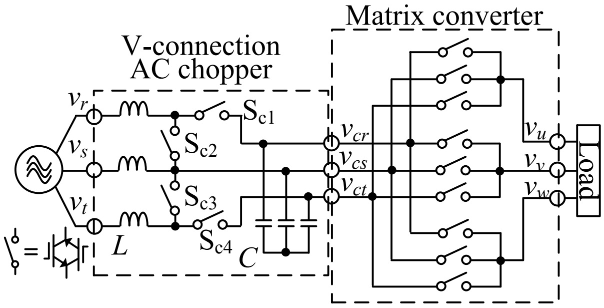


Fig. 2. Circuit configuration of the proposed circuit.

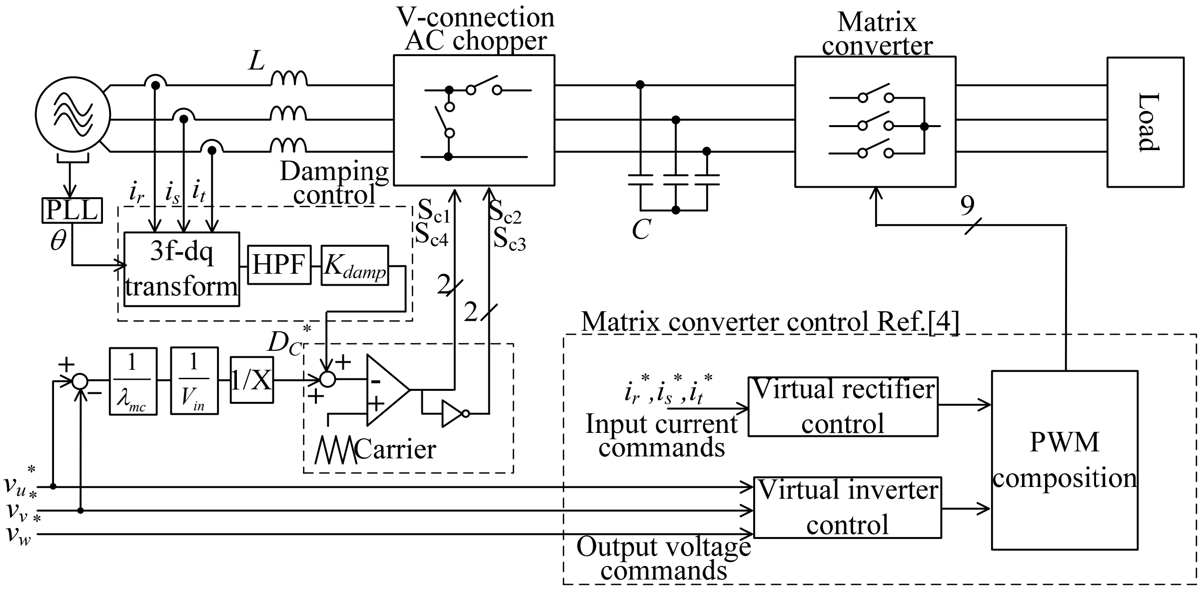


Fig. 3. Control block diagram of the proposed circuit.

III. Controller design

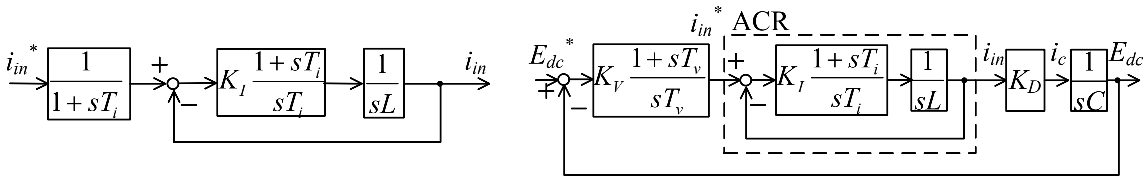
3.1 BTB system

Figure 4 shows the control block diagram of BTB system. i_{in} and E_{dc} are the input current and the DC link voltage in the BTB system, respectively. And also, i_c is the capacitor current in the smooth capacitor. Figure 4-(a) and 4-(b) show the control block diagram of ACR and AVR, respectively. The ACR is necessary for the control of the input current in the AC-DC conversion. In addition, the AVR is inserted into the ACR to control the DC link voltage along with the input current command. The transfer function of the ACR and the AVR are expressed by (2) and (3), respectively.

$$G_{ACR} = \frac{\frac{K_I}{LT_i}}{s^2 + \frac{K_I}{L}s + \frac{K_I}{LT_i}} \tag{2}$$

$$G_{AVR} = \frac{\dfrac{K_V K_D}{CT_V}}{s^2 + \dfrac{K_V K_D}{C}s + \dfrac{K_V K_D}{CT_V}} \tag{3}$$

where, the transient response of the ACR is faster than the AVR and the equation (3) is calculated by equaling the gain of the ACR to 1. Also, K_v and T_v are the proportional gain and the integrated time of the AVR, respectively. K_I and T_I are the proportional gain and the integrated time of ACR, respectively.



(a) ACR (b) AVR

Fig. 4. Control block diagram of BTB system.

3.2 Proposed circuit

Figure 5 shows the response block diagram of the V-connection AC chopper. K_v is the converter gain, which is defined as a half of the maximum output voltage in the V-connection AC chopper. T_{HPF} is the time constant of high pass filter (HPF). Then, the transfer function is expressed by (4).

$$G_{damp} = \frac{V_{out}}{V_{in}} = \frac{\dfrac{1}{\beta LC}s + \dfrac{1}{\beta LCT_{HPF}}}{s^3 + (\dfrac{1}{T_{HPF}} + \dfrac{K_v K_d}{L})s^2 + \dfrac{1}{\beta^2 LC}s + \dfrac{1}{\beta^2 LCT_{HPF}}} \tag{4}$$

The damping resistor R is calculated as resonance suppressed by the damping control. The transient response of the transfer function for the AC chopper with the damping resistor R is expressed by (5).

$$G_{resist} = \frac{V_{in}}{V_{out}} = \frac{\dfrac{R}{\beta \cdot L}s + \dfrac{1}{\beta \cdot LC}}{s^2 + \dfrac{R}{\beta^2 \cdot L}s + \dfrac{1}{\beta^2 \cdot LC}} \quad (5),$$

When the gain of the equation (4) is equal to (5) at resonance frequency, the damping resistor R is expressed by (6).

$$R = \sqrt{\frac{\beta^4 \cdot LCK_v{}^2 K_d{}^2 T_{HPF}{}^2}{[(\beta^2 + \dfrac{T_{HPF}{}^2}{LC})L^2C^2 - \beta^2 C^2 K_v{}^2 K_d{}^2 T_{HPF}{}^2]}} \quad (6),$$

where, the resonance frequency of the proposed circuit is changed by the V-connection AC chopper.

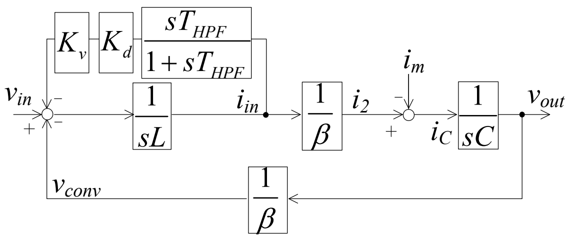


Fig. 5. Block diagrams for the input filter with a damping control.

3.3 Relationships between the control response and the capacitance

Figure 6 shows the gain characteristics of a board diagram comparison between the BTB system and the proposed circuit. Table I shows the calculation condition for the gain characteristics. The resonance frequency of the proposed circuit is set to 1/10 of the switching frequency. Note that the equivalent resonance frequency of the proposed circuit is decreasing with the boost-up ratio of the AC chopper. In this paper, in order to integrate the guide of the filter design, the capacitor C is picked up as the boost-up ratio of the chopper, which is equal to 1.

The design of the damping gain K_d is explained as following. In this paper, the damping gain in the damping control is designed to obtain the same characteristics when the damping resistor is used in the input filter. In other words, the gain of the equation (4) and the equation (5) are equally at the resonance angular frequency. Consequently, the damping gain K_d is calculated by (7).

$$K_d = \frac{2L\sqrt{\beta^2 + \frac{T_{HPF}{}^2}{LC}}}{\beta K_v T_{HPF}} \cdot \frac{\zeta}{\sqrt{4\zeta^2 + \beta^2}} \tag{7}$$

where, ζ is the damping factor and is expressed by (8).

$$\zeta = \frac{R}{2}\sqrt{\frac{C}{L}} \tag{8}$$

The damping gain K_d became 0.018 in the condition of Table 1 and equation (7).

It is a requirement that the response of the ACR is faster than the AVR. However, the transient response of the ACR is limited by the switching frequency. Therefore, the transient response of the AVR is also limited by the ACR.

On the other hand, the proposed circuit is unstable without applying the input current stabilization methods control (damping control in the filter) due to the resonance between the input reactor L and the filter capacitor C. Then, the maximum gain is equaled to 45 dB in the view of the input filter loss which is become the damping factor. On the other hand, the maximum gain of the proposed circuit with the damping control is 17.8 dB. Thus, the resonance between the input reactor and filter capacitor is suppressed by the damping control. In addition, it is confirmed that the damping control can suppress the resonance of the input filter without degrading the voltage transient response. Therefore, the filter capacitor depends on the response of the input filter. For this reason, the cut-off frequency of the filter is higher than the transient response frequency of the ACR. As a result, if the capacitance of the filter capacitor is decided by the voltage response, then the filter capacitor of the proposed circuit is smaller than the smooth capacitor of a BTB system.

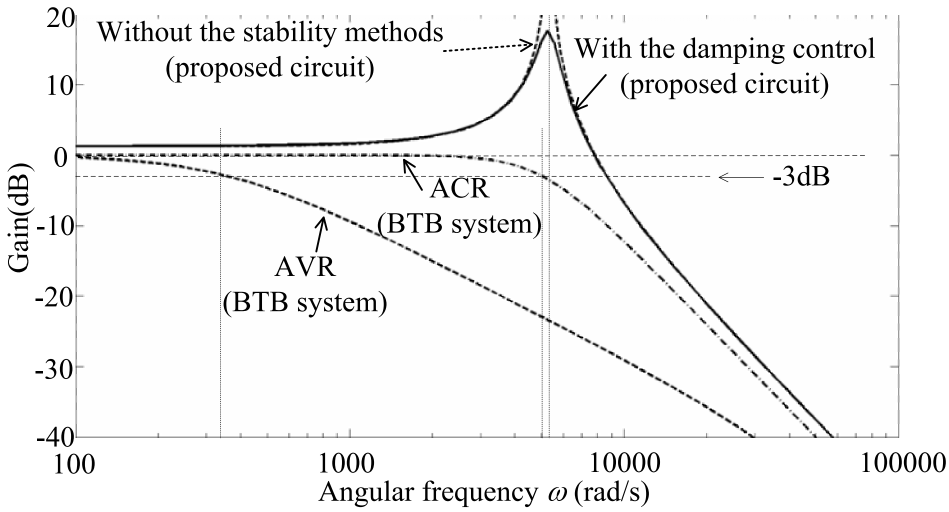


Fig. 6. Gain characteristics comparison between BTB system and the proposed circuit.

Table I : Calculation parameters

<table>
<tr><th colspan="3">BTB system</th><th colspan="2">Proposed circuit</th></tr>
<tr><td colspan="2">Input reactor L</td><td>7 mH</td><td>Input reactor L</td><td>2 mH</td></tr>
<tr><td colspan="2">Smooth capacitor C</td><td>470 μF</td><td>Filter capacitor C</td><td>13.2 μF</td></tr>
<tr><td colspan="2">DC voltage E_{dc}</td><td>283 V</td><td>Boost-up ratio β</td><td>1.15</td></tr>
<tr><td colspan="2">Converter gain K_D</td><td>0.866</td><td>Converter gain K_v</td><td>164</td></tr>
<tr><td rowspan="2">Response angular frequency ω</td><td>ACR</td><td>5000 rad/s</td><td rowspan="2">Resonance angular frequency ω_c</td><td rowspan="2">5300 rad/s</td></tr>
<tr><td>AVR</td><td>500 rad/s</td></tr>
<tr><td rowspan="2">Damping factor ζ</td><td>ACR</td><td>0.7</td><td rowspan="2">Damping gain K_d</td><td rowspan="2">0.018*1</td></tr>
<tr><td>AVR</td><td>0.7</td></tr>
<tr><td rowspan="2">Proportional gain</td><td>K_I</td><td>0.41*1</td><td rowspan="2">Integrated time of HPF T_{HPF}</td><td rowspan="2">3.18 ms</td></tr>
<tr><td>K_V</td><td>49 *1</td></tr>
<tr><td rowspan="2">Integrated time</td><td>T_I</td><td>0.28 ms</td><td rowspan="2">Switching frequency f_s</td><td rowspan="2">10 kHz</td></tr>
<tr><td>T_V</td><td>2.8 ms</td></tr>
</table>

*1 This gain is standardization value.

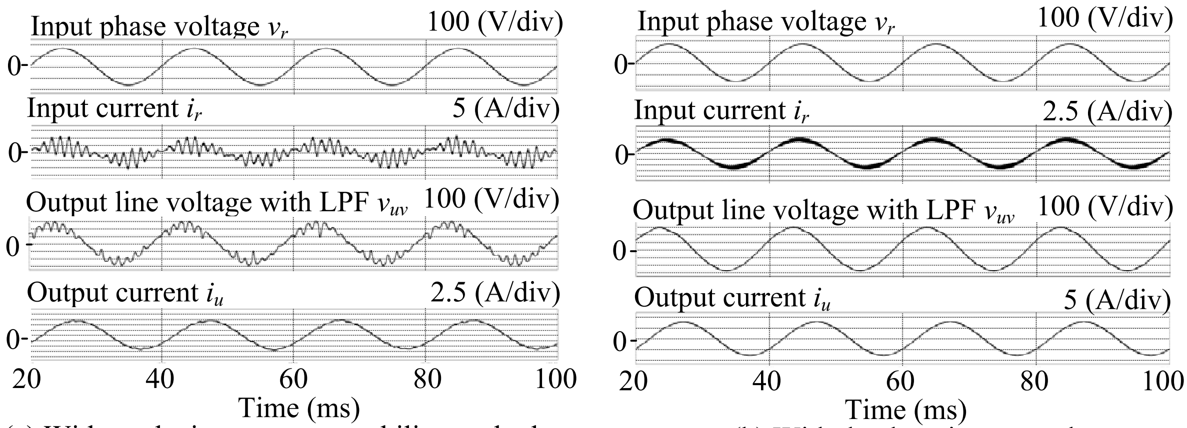
IV. Simulation and experimental results

4.1 Basic operations

4.1.1 Simulation results

Figure 7 shows the operation waveforms of the proposed circuit. Table 2 provides the parameters and the conditions for the simulation circuit. Figure 7(a) shows the operation waveform without applying the input current stability control method. Then, the total harmonic distortion (THD) of the input current and output voltage THD are 63.2 % and, 15.4 % respectively. It is confirmed that the resonance distortion occur in the input current waveform. On the other hand, Figure 7(b) shows the operation waveform, where the damping controls is applied in the AC chopper for the suppression on the resonant distortion. For these results, it is confirmed that the output voltage can increase to 27 V. Furthermore, the input current THD and output voltage THD can be improved to 6.6 % and, 1.2 % respectively.

Figure 8 shows the simulation results when the output voltage ratio changes from 0.8 to 1.2. The output voltage ratio is the ratio between the output voltage and the input voltage in the proposed circuit. The output voltage starts to change from 40 ms. Gradually, the output voltage is reached 1.2 time of the input voltage. The input current of THD is 11.1 %. The AC chopper is not switching before the 40 ms, that is before the voltage transfer ratio reaches the limit 0.866, the AC chopper remains at off-state. Therefore, the switch S_{c1} in Fig.8 shows no switching, and the switching loss is not occurred.



(a) Without the input current stability methods. (b) With the damping control.

Fig. 7. Operation waveforms by simulation.

Table II : Simulation parameters

Input phase voltage	115 V	LC filter	2 mH (2.36 %)
Input frequency	50 Hz		13.2 μF (11.1 %)
Carrier frequency	10 kHz	Boost ratio of chopper	1.15
Time constant of HPF T_{HPF}	3.18 ms	Voltage transfer ratio of MC	0.865
Output power	1.4 kW	Output frequency	50 Hz
Damping gain K_d	0.018	Load	R-L

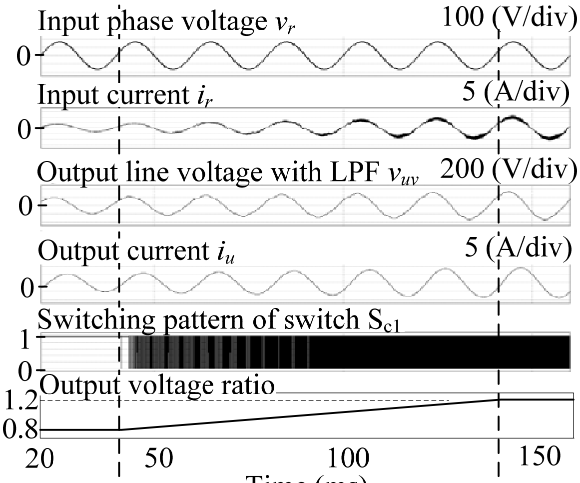


Fig. 8. Ramp response for the output voltage command.

4.1.2 Experimental results

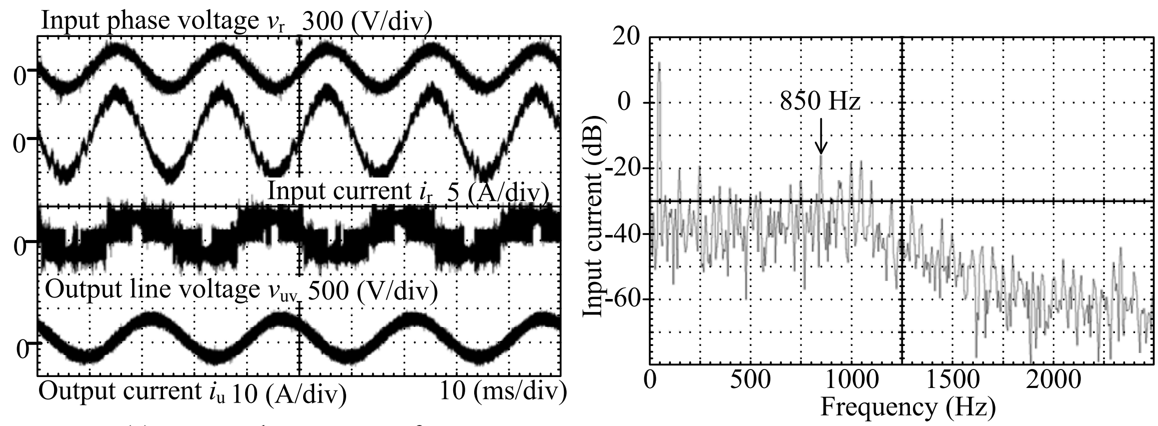
Figure 9(a) shows the experiment operation waveforms of the proposed circuit. Table 3 provides the parameters and the conditions for the experimental circuit. Note that the damping control is applied in this experimental set-up. As a result, it is confirmed that the voltage transfer ratio can be improved and the power factor is nearly to 1.

Figure 9(b) shows the harmonic analysis by Fast Fourier Transformation. Furthermore, the input current THD and output voltage THD are 7.6 % and, 1.58 % respectively.

The reasons why the input current THD of the experiment degraded in comparison with the simulation are following. The proposed circuit in the simulation uses an ideal switching pattern and ideal components. For this reason, the open circuit and the short circuit between the power source and the load are not considered. However, it is necessary to commutate the switching pattern to prevent the source and the load from short circuit or open circuit in the experiment. As a result, the input current has distortion due to the voltage error which is caused the switching commutation. Besides, there are commutation failures in the switching pattern because of the error on the voltage detection.

Figure 10 shows the transient response of the AC chopper at the starting operation. The AC chopper has not operated while the output line voltage command equals to 115 V. When the output line voltage command changed 200 V from 115 V, it is confirmed that the transient response of the input and output current are stable. Thus, the proposed circuit can stably operate during the transient response.

Figure 11 shows current THD characteristics based on the output power. Note that the damping control is applied in the V-connection AC chopper. It is confirmed that the output current THD is less than 2 %. On the other hand, the input current THD is less than 10 %. The input current THD becomes



(a) Input and output waveforms. (b) Harmonic analysis results of the input current.

Fig. 9. Operation waveforms of the proposed circuit.

Table III : Experimental parameters

Input phase voltage	115 V	LC filter	2 mH (2.36 %)
Input frequency	50 Hz		13.2 µF (11.1 %)
Carrier frequency	10 kHz	Boost ratio of chopper	1.15
Time constant of HPF T_{HPF}	3.18 ms	Voltage transfer ratio of MC	0.865
Output line voltage	200 V	Output frequency	40 Hz
Damping gain K_d	0.018	Load	R-L

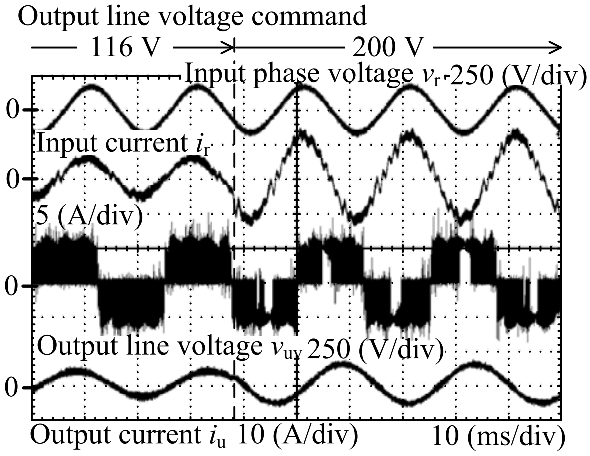


Fig. 10. Transient response of the chopper starting operation.

poor as the output power decrease. This is because once the output power reduces, although the harmonic distortion of the input current amplitude is constant, the fundamental amplitude of the input current becomes smaller. Besides that, the validity of the damping control is confirmed in all range of the output power.

Figure 12 shows the efficiency and power factor characteristics of the proposed circuit. As a result, it is confirmed that the maximum efficiency and power factor are 95.1 % and 0.996 respectively. In addition, the efficiency is over 95 % and the power factor is over 0.99 when the output power is higher than 1.2 kW.

Figure 13 shows the converter efficiency on a condition the output power is controlled to 1.4 kW constantly and the output line voltage is gradually increase proportional to the output frequency. When the output line voltage is less than 170 V, the proposed circuit could achieve high efficiency point of 95.7 %. As the output line voltage is larger than 170 V, the switching loss in the AC chopper occurs and the efficiency of the proposed circuit starts to reduce. Since, the switching loss increased due to the boost ratio in the AC chopper.

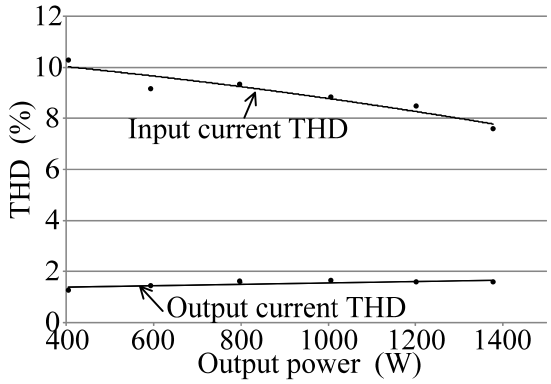


Fig. 11. THD characteristics to the output power.

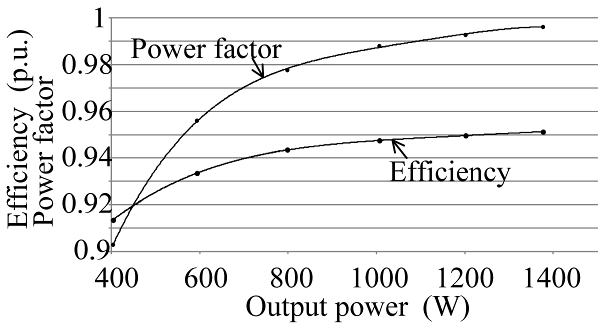


Fig. 12. Efficiency and the power factor characteristics to the output power.

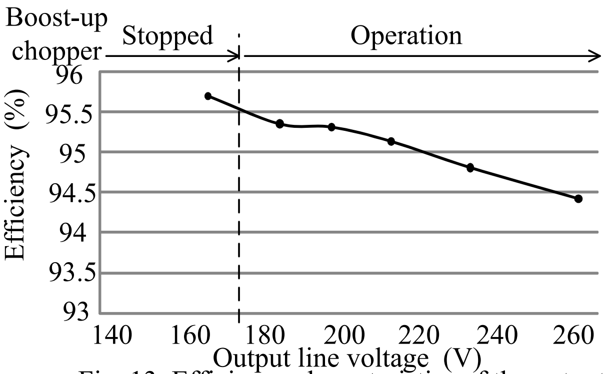


Fig. 13. Efficiency characteristics of the output voltage at constant output power of 1.4-kW.

4.2 Loss analysis

Figure 14 shows the loss analysis of the converter at 1.4 kW. The loss ratio of the AC chopper is equal to 25.2 % (15.8 W). On the other hand, the loss ratio of the matrix converter is equal to 52.6 % (33 W). In addition, the total loss of the input reactor and the filter capacitor is 22.2 % (14 W). The bi-directional switches are composed by using two IGBTs in this experimental circuit. For this reason, the efficiency is reduced due to the conduction loss from the free-wheeling-diode (FWD). If RB-IGBT can be applied as the bi-directional switches, the efficiency of the system can be improved. According to Figure 14, it is expected that the loss which is equal to 19.2 W (conduction loss of FWD) can be decreased. Thus, efficiency is expected to improve by 1.3 %.

Figure 15 shows the loss comparison between the BTB system and the proposed circuit. Note that the IGBTs of the same switching characteristics are using in the proposed circuit and the BTB system in order to compare the loss equally. In addition, the switching devices in the proposed circuit use RB-IGBT. In other word, the conduction loss of FWD in the proposed circuit is not considered. According to the loss analysis, the converter loss of the proposed circuit is similar to the inverter or the rectifier in BTB system. On the other hand, the total loss of the chopper in the proposed circuit is less than the rectifier or even the inverter due to the low conduction. The chopper circuit is composed by the type of V-connection. For this reason, the number of devices in the chopper where the current passes through is 2/3 less than the rectifier. Therefore, it is confirmed that the proposed circuit which inserted in V-connection AC chopper can achieve a higher efficiency than the BTB system.

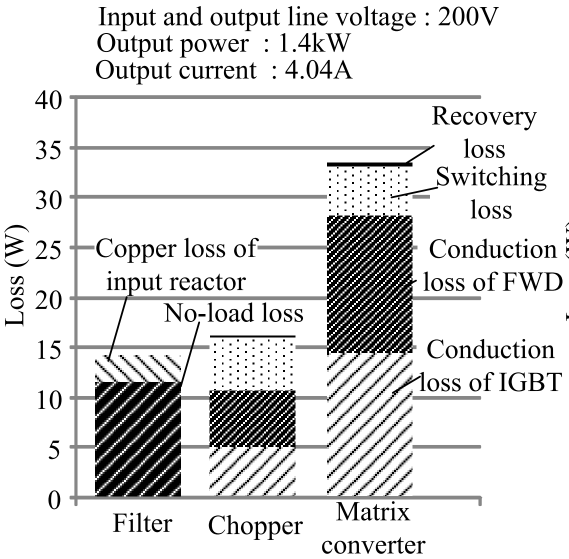


Fig. 14. Property of the loss.

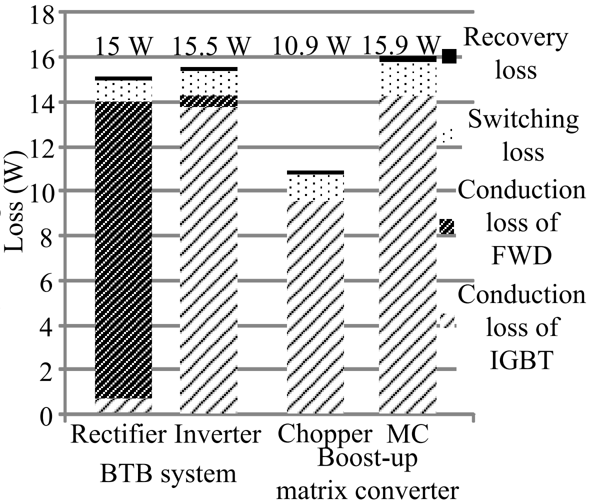


Fig. 15. Loss analysis of BTB system and proposed circuit.

V. Conclusions

This paper proposed a circuit topology for the MC with boost up functionality by using a V-connection AC chopper. The advantages of the proposed circuit are following;

- The proposed circuit has the advantages of the origin MC such as small size, light-weight and long life-time, even an AC chopper is added into the input side.
- The MC and the V-connection chopper can be controlled independently.
- High speed feedback controller such as AVR is not necessary for the proposed circuit. Consequently, the filter of the proposed circuit can be designed with a small filter capacitor.

In order to stabilize the input current, the damping control is applied in the chopper. The proposed circuit remains high efficiency even damping control is applied in the filter because the resistance loss of damping resistor is low.

The proposed circuit is experimented by using a 1.4 kW prototype. A unity input power factor is obtained. Besides, the voltage transfer ratio could be improved by the boost-up operation. The input current THD and output current THD are 7.6 % and 1.58 % respectively. The experimental results confirmed that the proposed circuit could achieve a maximum efficiency and power factor of 95.1 % and 0.996. Therefore, the fundamental operation of the proposed circuit is confirmed by the experimental results. It is confirmed that the loss of the proposed circuit is less than that of the BTB system.

In future works, the damping gain and the input filter will be optimized.

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