Input Current Stabilization Control of a Matrix Converter with Boost-up Functionality

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***Abstract*-- This paper proposes a circuit topology of a matrix converter that adding a boost up function in the input side. The proposed circuit combines the matrix converter with a V-connection AC chopper. A conventional control method can be applied in this matrix converter, so called the virtual indirect method. In order to suppress the input filter resonance, this paper discusses about the input filter design with a damping resistor. In addition, this paper also proposed a stabilization control for the input current that is using a V-connection chopper. The basic operation and validity of the proposed method is confirmed by the simulation and experimental results. The total loss of the proposed circuit is 20 % less than that the loss of the conventional back to back system.**

***Index Terms*—Matrix converter, Damping control, V-connection AC chopper**

I. INTRODUCTION

A matrix converter that is well known to convert an AC power supply voltage directly into an AC voltage of variable amplitude and frequency without large energy storages, such as electrolytic capacitors, have been actively studied recently [1-12]. Practically applying of matrix converters into industrial, the following advantages are found as compared with a back to back converter (PWM rectifier and PWM inverter); (i) light-weight and long-life due to no passive components in the circuit (ii) high efficiency power supplies because of less switching devices. The matrix converter is expected to apply in the hybrid electric vehicle system and the wind power generator system in the future.

However, one disadvantage of the matrix converter is the voltage transfer ratio, which defines the ratio between the output voltage and input voltage, is being constrained to 0.866. As a consequence, the output current of the matrix converter is higher than the back-to-back (BTB) type converter, under the same output power. Consequently, the motor loss and the converter loss will be increased. Besides, the low voltage transfer ratio also limits the applications of the matrix converters.

There are some discussions to improve the voltage transfer ratio for the matrix converters. One of the easy solutions is to improve the voltage transfer ratio by connecting a transformer between the power supply and the matrix converter. However, the commercial transformer applied in the power grid frequency is bulky.

In the Ref. [8], the matrix converter is proposed to operate in over modulation range. The voltage transfer ratio successfully improved to 0.94. However, the input current and the output current contain of large distortions. Additionally, the over modulation method can not boost up the input voltage. Therefore, the use of a matrix converter instead of the BTB system in the future, the boost up functionality is necessary for the specific application, which allows changes in the input voltage.

On the other hand, a Matrix-Reactance Frequency Converter (MRFC), which consists of a matrix converter and an AC chopper, has been studied [9]. In the Ref. [9], the output voltage of the MRFC can set higher than the input voltage. However it seems that the MRFC requires many components due to the insertion of the boost up reactor and capacitor. In addition, it is difficult to control the MRFC because the matrix converter and the chopper need to synchronize with each other.

This paper proposes a circuit topology which connects a V-connection AC chopper in the input side of the matrix converter that comes with a boost up functionality. The only additional component of this proposed circuit is bidirectional switches because the input filter reactor is used as a boost reactor in this proposed method. One of the features in this proposed circuit is that an automatic voltage controller for the chopper is not required. As a result, the capacitor in the boost-stage can become smaller than the DC capacitor in the BTB system. Moreover, this proposed circuit keeps the advantages of a matrix converter such as small size, light-weight and long-life time. In order to suppress the input filter resonance, a stabilization control is proposed in this paper. In addition, this paper also discusses about the input filter design method for the proposed converter. The fundamental operation and validity of the proposed method is confirmed by the simulation, experimental results and loss analysis.

II. CIRCUIT TOPOLOGY AND CONTROL STRATEGY

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 in order to smooth the DC link voltage. 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.

This system is very flexible in term of voltage condition between the input and the output side since both converters are voltage type converters. However, the electrolytic capacitor in DC link part gives known problems such as large volume, high cost and short lifetime in high temperature.

Figure 2 shows the proposed circuit diagram. The proposed circuit connects a V-connection AC chopper in the input side of the matrix converter. The additional components are based on 4 reverse blocking IGBTs (RB-IGBT) that is mainly constructed by silicon and diodes. Additionally, the proposed circuit uses a minimum amount of switching devices for this approach. The proposed circuit does not require voltage control in the input capacitor since both the input side and thr output side of the V-connection chopper are AC voltage; i.e. the voltage control of the V-connection chopper is an open loop control. Therefore, the capacitor value does not dominant by the voltage control response and the current response. As a result, the proposed circuit does not affect the size and the weight of the origin structure of a matrix converter.

The maximum output voltage of the matrix converter 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 switch when the output voltage command is lower than 0.866 of the input voltage. That is, in the low voltage transfer ratio, the proposed circuit is able to obtain high efficiency obviously as same as original matrix converter.

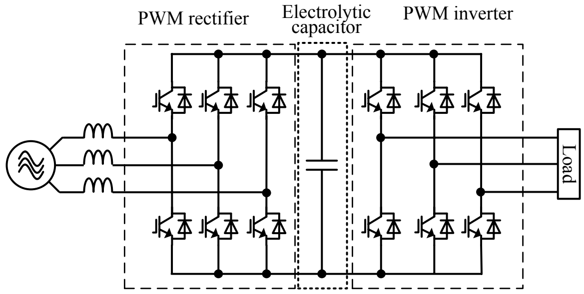


Fig. 1 Back to Back converter.

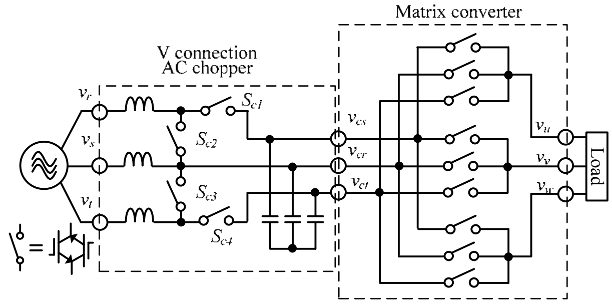


Fig. 2 Proposed circuit.

III. STABILIZATION METHOD OF INPUT CURRENT

The resonance between the input reactor and the input capacitor occurs in the input side. In particular, when the resonant frequency is higher than the power grid frequency, the variation by the resonance is appeared on the input current and the capacitor voltage. In a conventional matrix converter, the damping resistor, which is connected in parallel to an input reactor, is used to suppress the input current resonance. In addition, a stabilization control method of the input current has been studied in Ref. [10-11].

On the other hand, the proposed converter connects a V-connection chopper in front of the matrix converter. Furthermore, the current waveform of the filter capacitor is a PWM waveform and the terminal voltage of the input reactor is also a PWM waveform. Therefore, the damping resistor will cause large loss because of many harmonics are included in the voltage or current. In the next section, the location of the damping resistor will be discussed to solve the large loss due to the damping resistor connection.

A. Location of a Damping Resistor

Figure 3 shows single phase equivalent circuits of the AC chopper and high frequency equivalent circuits. In equivalent circuit, a matrix converter is represented as a current source of I_m because the input control characteristic of the matrix converter is same as the current source type converter.

Four various connection patterns for the damping resistor are shown in Fig.3 (a)-(d). The loss of the damping resistor can be separated into the fundamental frequency component and the switching frequency component of the input current.

At fist, the power loss of the damping resistor in Fig.3 (a) is discussed. In high frequency equivalent circuit, a chopper part and a current source representing a matrix converter is concluded as a voltage source of v_s. Then, the voltage source of v_s is obtained by Fourier transforms. The fundamental frequency of the switching function for S_1 is calculated by

$$v_s = v_o S_1 = v_o \left(1 + \frac{2}{\pi} \sum_{n=1} \frac{1}{\mathrm{n}} \cos n\pi \sin n\pi D \cos n\omega_s t\right) \qquad (1),$$

where, ω_s is the switching angular frequency and D is a duty ratio of the switch S_1. n is the order of the switching frequency. In this paper, n=1 and v_o is the capacitor voltage in output side of the chopper. Therefore, the RMS value of V_s is given by

$$V_s = \frac{V_0}{\pi} \sin \pi D \qquad (2),$$

where V_o is RMS value of the output voltage. From the equivalent circuit, the damping resistor is determined by

$$R = 2 Z_0 \xi \qquad (3),$$

where Z_0 is the characteristic impedance of the input filter and from the damping factor ξ. Next, the reactor current I_s of high frequency component is obtained by the circuit equation based on Fig. 3(a)-(ii). It should be noted that the input current is expressed by Z_0 and ξ instead of the damping resistor. The input current I_{in} for the fundamental frequency component can be calculated from the output power of the AC chopper that is divided by the input voltage. Consequently, the damping resistor loss $P_{loss\_Lseries}$ is obtained by

$$P_{loss\_Lseries} = RI_{in}^{2} + RI_{s}^{2} = \frac{2\xi}{Z_o}I_{in}^{2} + \frac{2\xi}{Z_o}\frac{V_s^{2}}{4\xi^{2}+(\frac{\omega}{\omega_c})^{2}} \quad (4),$$

where ω_C is the cut off angular frequency of the input filter, which is determined by

$$\omega_C = \frac{1}{\sqrt{LC}} \quad (5),$$

The characteristics impedance Z_0 is determined by

$$Z_0 = \sqrt{\frac{L}{C}} \quad (6),$$

Similarly, the loss of the damping resistor, which is connected in parallel to the reactor as shown in Fig. 3(b), is calculated by the same formula.

Secondly, the power loss of the damping resistor in Fig.3(c) is discussed. From the super position principle, the high frequency equivalent circuit can be separated to the power loss by the chopper and the matrix converter. Additionally, the reactor L' transforms a reactor value to the output side from the input side. It is determined by

$$L' = \frac{L}{(1-D)^2} \quad (7),$$

where D is the duty ratio of the switch S_1.

In this case, the chopper can not be expressed by a voltage source as previously discussed because the voltage fluctuation of the capacitor can not be neglected. For the voltage source, the chopper is represented by a current source of i_{cp}, which is the current of input reactor. Then, the reactor current i_{cp} is obtained by

$$i_{cp} = i_{in}S_1 = v_o(1+\frac{2}{\pi}\sum_{n=1}\frac{1}{\mathrm{n}}\cos n\pi \sin n\pi D \cos n\omega_s t) \quad (8),$$

From Fig.3(c)-(ii), the power loss P_{loss_Cpara} is the current flowing into the resistor for each circuit which is given by

$$P_{loss\_Cpara} = \frac{2\zeta Z_0}{4\zeta^2(\frac{\omega}{\omega_C})^2+1}(i_{cp}-i_m)^2 \quad (9),$$

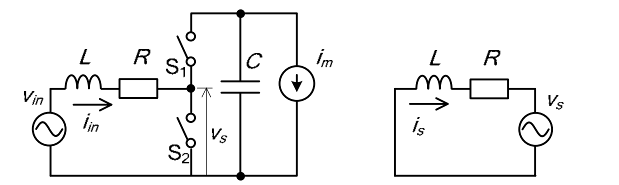
Similarly, the loss of the damping resistor, which is connected in parallel to the reactor as shown in Fig.3 (d), is calculated by the same formula in Fig. 3(c).

Finally, the optimization of the location of the damping resistor is decided by the power loss of the damping resistor.

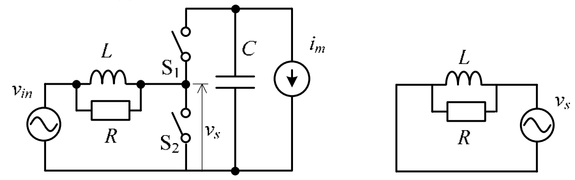
Figure 4 shows the relations between the damping resistor loss and the damping factor. Table 1 shows the calculation parameter for Fig.4. Firstly, when the damping resistor is connected in parallel to the reactor, the damping resistor loss becomes larger because the reactor voltage contains the switching ripple caused by the chopper PWM operation. Secondly, the damping resistor loss is also increased in the following two connections; when the damping resistor connects to the capacitor in parallel and the reactor in series, because the damping resistor loss includes the fundamental component. As a result, the minimum loss is only achieved when the damping resistor is connected to the capacitor in series. However, the loss in the damping register is still large when the damping factor is set to

TABLE I
PARAMETERS

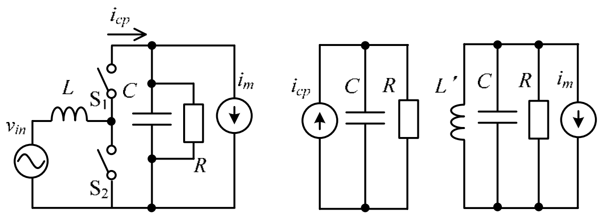
Input voltage	200 [V]	LC filter	2 [mH]
Input frequency	50 [Hz]		40 [μF]
Carrier frequency	10 [kHz]	Output power	1.5 [kW]
Output frequency	50 [Hz]	Boost ratio	1.23



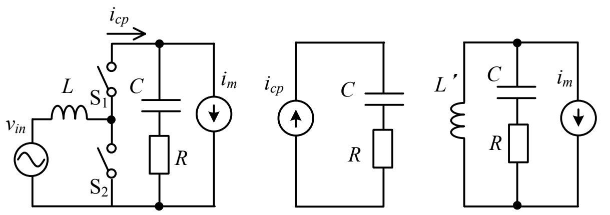
(i) Single phase equivalent circuit (ii) High frequency equivalent circuit
(a) Resistor connected to reactor in series.



(i) Single phase equivalent circuit (ii) High frequency equivalent circuit
(b) Resistor connected to reactor in parallel.



(i) Single phase equivalent circuit (ii) High frequency equivalent circuit
(c) Resistor connected to capacitor in parallel.



(i) Single phase equivalent circuit (ii) High frequency equivalent circuit
(d) Resistor connected to capacitor in series.
Fig. 3 Equivalent circuits of the AC chopper.

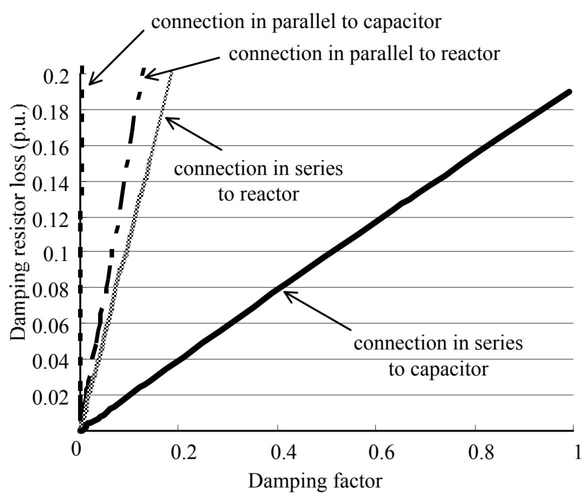


Fig. 4 Relation between the damping resistor loss and damping factor.

more than 0.3 as shown in Fig.5. Since the damping resistor loss can not be neglected, a damping control is required in the chopper control.

B. Design of the LC Filter

The damping resistor is used to suppress a resonance in the LC filter. The main components in the input current and voltage ripple are around the switching frequency. In order to determine the filter design, the ripple component of the switching frequency is evaluated in this paper.

The amplitude of the ripple current and ripple voltage on the input filter are calculated by the equivalent circuit shown in Fig.3 where the damping resistor is not connected. The maximum value of the current ripple and the voltage ripple is expressed by the following respectively,

$$I_{rip} = \frac{\sqrt{2}V_o}{\pi\omega_s L}\sin n\pi D \qquad (10),$$

$$V_{rip} = \frac{\sqrt{2}I_{in}}{\pi\omega_s C}\sin n\pi D \qquad (11).$$

It is confirmed that the voltage ripple and the current ripple is decreased by increasing the input reactance and the filter capacitance.

Figure 5 shows the voltage and current ripple characteristics for the capacitance. Fig. 5 was calculated according to the conditions in Table 2. It is noted that the inductance of the reactor is changed according to the capacitance because the cutoff frequency of the input filter is set to 1 kHz constantly. The capacitance is not only normalized by the input impedance, but also the voltage and current ripple are normalized by the rated output voltage and the rated input current. There is a trade off relationship between the voltage ripple and current ripple against the capacitance. It is important to choose the balance point to optimize the performance of the input filter. Thus, the author suggests capacitor of 3.35 % is the most suitable parameter.

C. Damping Control of the Input Current

In order to suppress the oscillation in the input current that is caused by the resonance in the input filter, a stabilization control for the matrix converter has been proposed in [10]-[11]. In these papers, the distortion component of the terminal voltage is removed by using a band pass filter (BPF). After that, the distortion components are subtracted by the input current command. Since the proposed circuit uses the V-connection chopper, the stabilization control should be applied to the chopper control instead of the matrix converter.

Figure 6 shows the control block diagram for the proposed circuit. The applied control method for the matrix converter is the virtual indirect control method which can be referred in [7]. The matrix converter and the V-connection chopper can be easily controlled independently. The proposed stability control is implemented on the d-q frame of the ac chopper control. The fundamental frequency component on the d-q frame becomes a constant value, i.e. DC signal. In addition, the

TABLE II
PARAMETERS

Input voltage	200 [V]
Input frequency	50 [Hz]
Carrier frequency	10 [kHz]
Boost ratio	1.23
Output power	1.5 [kW]
Cut-off frequency	1 [kHz]
Output voltage	246 [V]
Input current	4.3 [A]

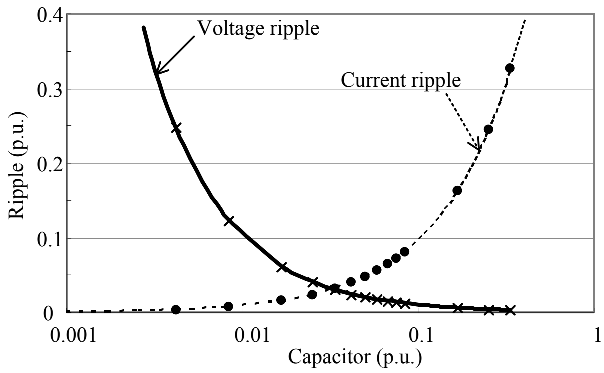


Fig. 5 The voltage and current ripple characteristics.

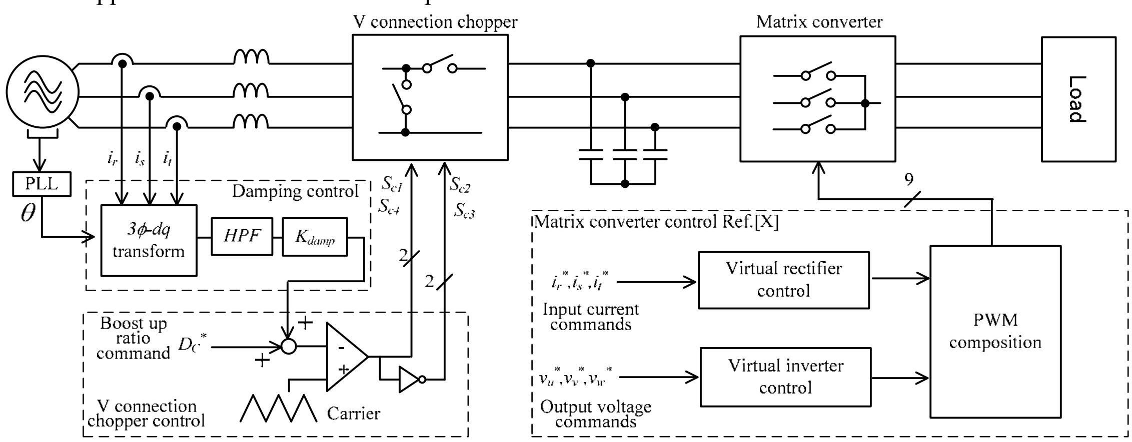


Fig. 6 Control block diagram of the proposed circuit.

harmonics components are appeared as ripple components. The distortion component of the input current is extracted by using a high pass filter (HPF). After that, the distortion component is added to the chopper command D_c^*. It should be noted that the proposed control does not require a high speed feedback regulator. It means that the capacitor and the boost-up reactor are not dominated by the control response of the input current and the capacitor voltage.

IV. Simulation and Experiment Results

A. Simulation results

The operation of the proposed circuit is demonstrated by the simulation results. Table 3 provides the parameters and the conditions for the simulation circuit. The cut-off frequency of the input filter was set to 1/10 of the switching frequency. Note that the damping resistor is not used in the simulation.

Figure 7 shows the waveforms of the proposed circuit. In the Fig. 7(a), the damping control is not applied. Therefore the input current has large oscillation based on the LC resonance. The input current of THD (Total harmonic distortion) is 7.6 %. On the other hand, in Fig. 7(b), the large oscillation components are suppressed in comparison with Fig. 7(a). As a result in Fig. 7 (b), it is confirmed that the input current and output voltage THD are 6.6 %, 1.2 % respectively.

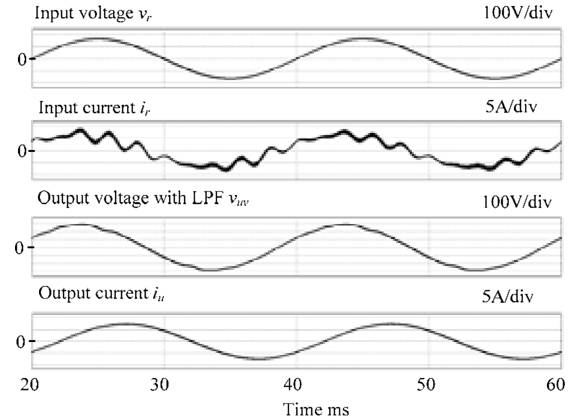
Figure 8 shows the simulation results when the output voltage ratio changes to 1.2 from 0.8. The output voltage starts to change from 40 ms, gradually. The output voltage is reached 1.2 time of input voltage. The input current of THD is 11.1 %. The chopper is not switching until the 40 ms. Thus, the switching loss is not occurred.

Figure 9 shows the loss analysis of the proposed circuit with damping resistor connected to the reactor in series by using a circuit simulator (PSIM, Powersim Technologies Inc) and a DLL file (Dynamic Link Library) [12]. The reverse blocking IGBT (RB-IBGT) is used for the proposed system in this simulation. The input current oscillation is suppressed by the damping resistor only. In this case, the damping resistor loss becomes larger as shown in Fig.9. Therefore the input current oscillation cannot be suppressed by using the damping resistor only, this will affect the features of matrix converter.

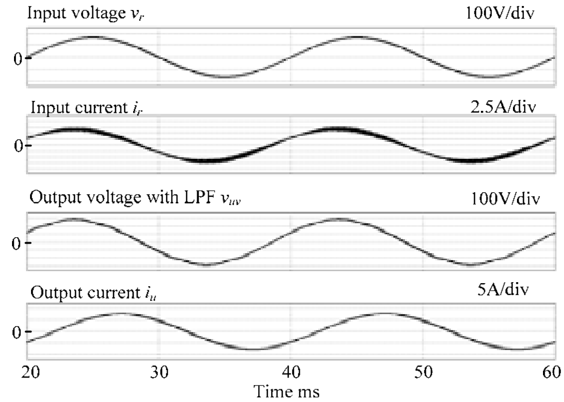
Figure 10 shows the loss analysis between the BTB system and the proposed circuit. The damping control is applied for proposed circuit. The damping resistor loss decrease drastically. In addition, the proposed circuit could decrease the switching loss by about 2/3 in compared with the BTB system. In one switching cycle, the number of switching for the proposed circuit is 8 times; however the number of switching is 12 times in the BTB system. Therefore, the loss in the proposed circuit is lower than the BTB system. These simulation results confirmed the validity and fundamental operations of the proposed circuit.

TABLE III
Simulation parameter.

Input voltage	200 [V]	LC filter	2 [mH]
Input frequency	50 [Hz]		40 [μF]
Carrier frequency	10 [kHz]	Output power	1.5 [kW]
Output frequency	50 [Hz]	Load	R-L



(a) Input and output waveforms without damping resistor and damping control.



(b) Input and output waveforms with damping resistor and damping control.

Fig. 7 Simulation results of the proposed circuit.

TABLE IV
Simulation parameter.

Input voltage	200 [V]	LC filter	2 [mH]
Input frequency	50 [Hz]		13.2 [μF]
Carrier frequency	10 [kHz]	Output power	1.5 [kW]
Output frequency	50 [Hz]	Load	R-L

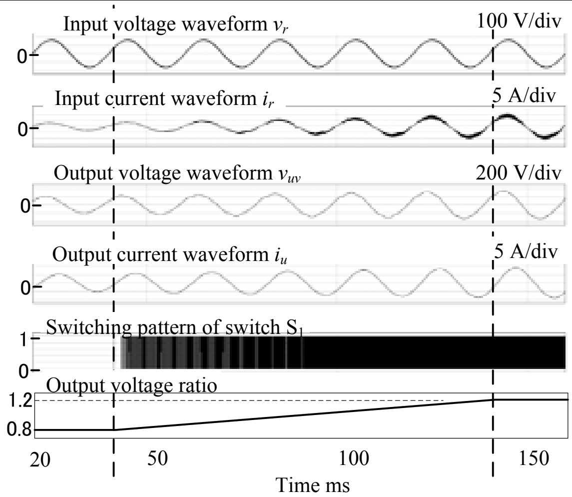


Fig. 8 Simulation results of the proposed circuit.

B. Experimental results

Figure 11 shows the experimental result of the proposed circuit. Table 5 shows the parameters of the experiment. The input voltage is increased to 1.25 times by the AC chopper in proposed circuit.

However, the input current i_r has distortion which is due to the commutation failure is occurring when cross point of the filter capacitor voltage magnitude. Although, the commutation failure will be decreased by the commutation method which is combined the voltage commutation and the current commutation [13].

Additionally, the input current and the output voltage waveforms will be improved by the damping control.

It should be noted that the output line voltage v_{uv} is observed by using a low-pass filter of 1.2-kHz cut-off frequency to observe the low frequency component distortion.

V. CONCLUSIONS

This paper proposed a circuit topology for the matrix converter with boost up functionality and the stabilization method in the input current control. The proposed circuit combines a matrix converter with a V-connection AC chopper. The advantages of the proposed circuit are following;

- The proposed circuit has advantages of the matrix converter such as small size, light-weight and long-life time, even added a chopper in the input side.
- The matrix converter and the V-connection chopper can be controlled independently.
- The loss of the proposed circuit is lower than the BTB system.

In addition, this paper discusses about the input filter design method for the proposed circuit. First, in order to suppress the resonance between the reactor and the capacitor in the input filter, the damping resistors are inserted. When the damping resistors are connected to the capacitor in series, it is suitable in terms of high efficiency. Secondary, the design method of the LC filter is discussed. The LC filter is designed from the voltage and current ripple characteristics. As a result, the capacitor of 3.35 % is the most suitable parameters.

In future works, the commutation failure will be decreased by the commutation method which is combined the voltage commutation and the current commutation. Furthermore, the input current and the output voltage waveforms will be improved by the damping control.

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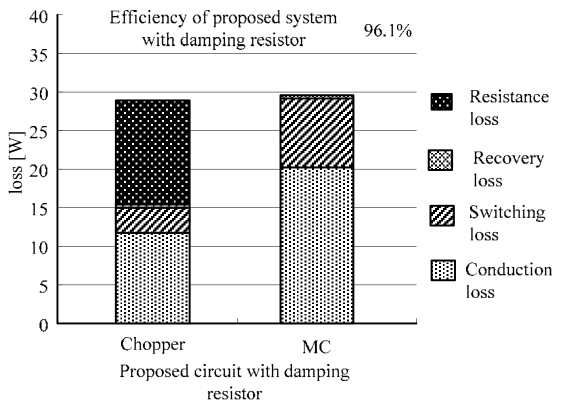

Fig. 9 Loss analysis of proposed circuit with damping resistor.

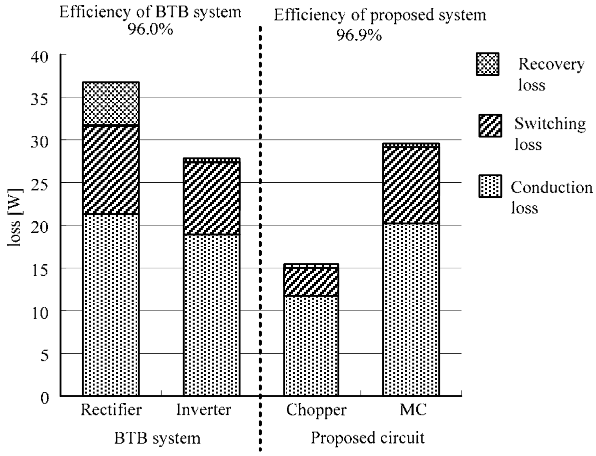

Fig.10. Loss analysis of proposed circuit and BTB system.

TABLE V
Circuit parameter.

Input voltage	90 [V]	LC filter	2 [mH]
Input frequency	50 [Hz]		19 [μF]
Carrier frequency	10 [kHz]	Boost ratio of chopper	1.25
Output frequency	50 [Hz]	Transfer ratio of MC	0.75
Damping resistor	26 [Ω]	Load	R-L

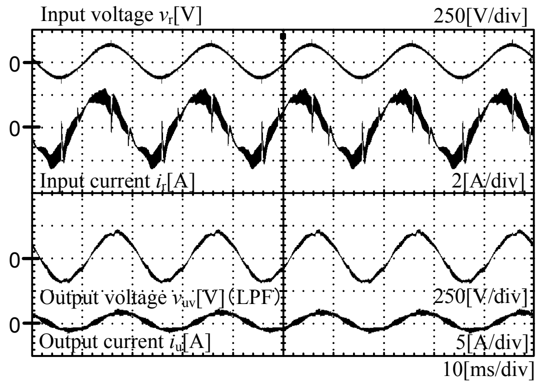

Fig. 11 Experimental results of the proposed circuit.

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