A Novel Control Strategy for a Combined System Using Both Matrix Converter and Inverter without Interconnection Reactors

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***Abstract*— This paper proposes the control strategy of a matrix converter and a voltage type inverter in parallel system which becomes unnecessary of interconnection reactors. The proposed control strategy divides the operation time of each converter to every carrier cycle. Further the output voltage of the combined system and the power distribution ratio of each converter are controlled, simultaneously. In addition, the sinusoidal input current waveform is obtained. The operation time of each converter is divided in one carrier cycle. Thus, interconnection reactors are not required. These new proposals are confirmed by the simulation and experimental results.**

I. Introduction

Recently, to improve the global environment problem, power converters require high efficiency. In particular, there has been a strong demand for high efficiency and downsizing of three-port interconnection converters with an AC and a DC power source such as, hybrid electric vehicles systems consisting of a generator, motor and battery, and the power grid back up systems using an engine generator and a battery [1].

Generally, a PWM rectifier, a DC chopper and an inverter system are used as a combined system of an AC and a DC power source. However, an electrolytic capacitor is needed as an energy buffer for DC link part in this system. The electrolytic capacitor results that the circuit is large-size, short lifetime and high cost. One of possibility to solve these disadvantages is application of matrix converters, which can directly convert AC to AC without the need of large electrolytic capacitors [2-3]. However, it is difficult to apply a matrix converter to an interconnection system consisting of an AC and a DC power source, because matrix converters have no DC link part in the main circuit.

There are some approaches to interconnection systems using other type matrix converters known as indirect matrix converters [4]. The indirect matrix converter has a DC stage without a capacitor and can also obtain high efficiency in comparison with conventional systems that consist of a PWM rectifier and an inverter. However, the efficiency of a conventional matrix converter using nine AC switches is higher than an indirect matrix converter.

On the other hands, there is another approach using a nine-switch matrix converter was proposed in Ref. [5]. A voltage type inverter is connected to input side of a matrix converter. However, in conventional systems, there are problems such as large-sized and needed maintenance because the snubber circuit is needed in a direct power converter. The snubber circuit causes large volume and high cost.

This paper proposes a novel control strategy for a three-port system of AC to AC and DC to AC conversion using a nine switch matrix converter and an inverter. The inverter with the battery is connected in parallel to the matrix converter in place of a snubber circuit. In other words, the proposed system is a delta configuration system among a generator, a battery, and a motor. This system can realize the most efficient power conversion between each power source because there is only one power converter between each power source. Moreover, the proposed system does not require an interconnection reactor, because the matrix converter operation is perfectly divided from the inverter operation by a gate-blocking signal.

There are two methods to control a matrix converter known as a indirect control [6-7], and a space vector PWM[2-3]. The operation time of each converter must be switched at high speed in order to keep a sinusoidal wave form for the input current. The indirect control is used to the matrix converter because a triangular wave comparison control [8] is used for parallel inverter. Then, the operation time of each converter is divided for every carrier cycle. An operation time division ratio is determined from output voltage and a power distribution ratio of each converter.

This paper describes the features of the proposed system and the proposed control method, and provides experimental results to demonstrate the validity of the proposed system.

II. The conventional configuration

A. A PWM rectifier and inverter system

Fig.1 shows a conventional PWM rectifier and inverter system with DC chopper for a DC power source. This system requires a large electrolytic capacitor in DC link part. This system is very flexible for the input and output voltage condition. However, the problem for an electrolytic capacitor in DC link part is large volume, short lifetime in high temperature and high cost.

B. A system using an indirect matrix converter

Fig. 2 shows the system using an indirect matrix converter. A DC/DC converter is added between an AC/DC converter and a DC/AC converter in this system configuration. The advantage of this system is that the efficiency is higher than a conventional PWM rectifier and inverter system. In addition, an indirect control is lower cost than a conventional matrix converter using nine-switch because a conventional IGBT module can be applied. Thus, easy commutation can be achieved because pulse pattern of the AC/DC converter does not require overlap time. However, the efficiency of this system is lower than the conventional matrix converter. Because the number of power conversions is needed twice between each power source.

C. A system connecting an inverter to input side of a matrix converter

Fig.3 shows the system connecting an inverter to the input side of the matrix converter. The characteristic of this system is that an input filter becomes unnecessary. However, the efficiency between the battery and the load is not so high because this system requires twice power conversion between a battery and load. In addition, the snubber circuit becomes large in order to absorb the energy of an inductive load in the protect operation of the matrix converter.

D. A general parallel system of a power converter

Fig. 4 shows the configuration of a conventional parallel connection system using interconnection reactors. A parallel connection system can easily increase the power rating. Interconnection reactors suppress the short circuit between parallel converters [9-13]. However,

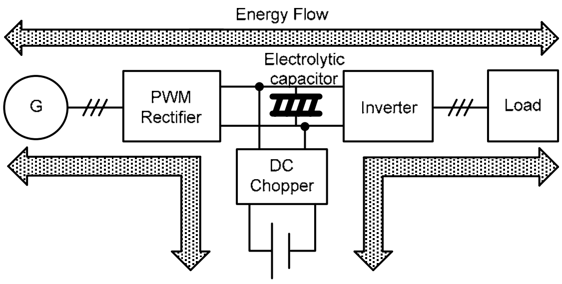

Fig. 1 Conventional PWM rectifier and inverter system with dc chopper

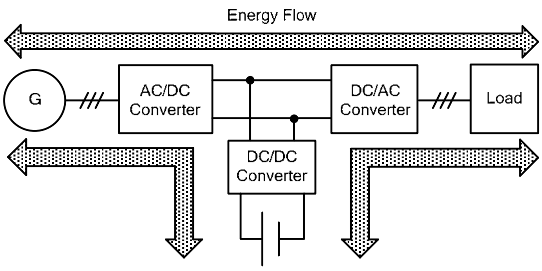

Fig.2 System configuration with an indirect matrix converter

interconnection reactors are large and heavy. In addition, the interconnection reactor results losses increasing.

III. THE PROPOSED CONFIGURATION

Fig.5 shows the configuration of the proposed system. The proposed system is a delta configuration system which is connected by the diode rectifier, the inverter and the matrix converter. Then, this system can directly convert among each power sources of a generator, a battery, and a motor. In this paper, the power converter between the generator and battery is used as the diode rectifier because the generator mainly charges the power to the battery. It is noted that if the system requires the generator is driven by the battery, the PWM rectifier can be applied.

The most significant characteristic in the proposal system is that the proposed system does not require the interconnection transformers or reactors at the connection point of the matrix converter and inverter because the time

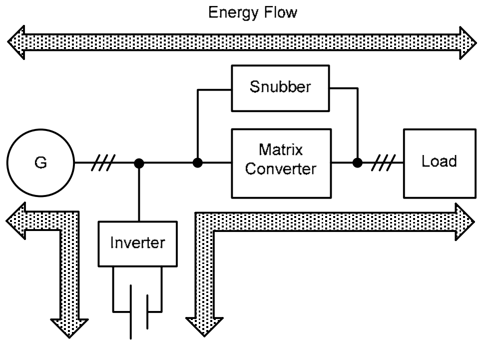

Fig.3 System configuration of the combined system of a matrix converter with an inverter at the input side

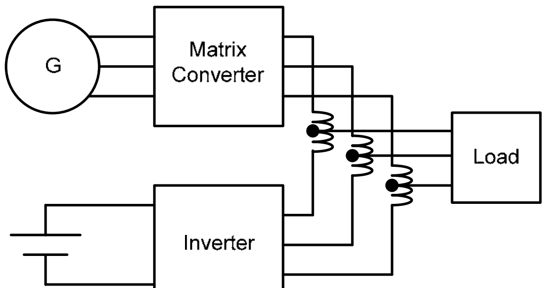

Fig.4 Parallel multiplexing system using interconnection reactors.

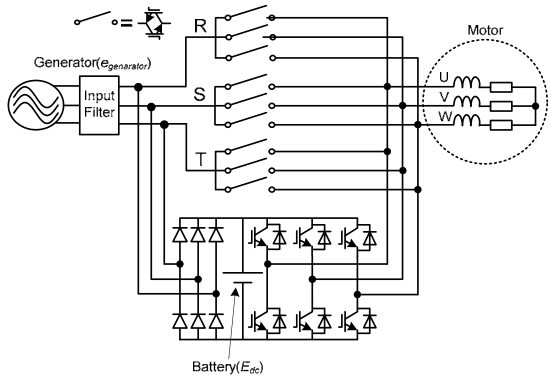

Fig.5 The proposed system using a matrix converter and an inverter without interconnection reactors.

sharing operation of the matrix converter and inverter is achieved during one carrier cycle. Furthermore, the chip temperature of a switching device in the system can be kept at low temperature because the output current of the proposed system can be distributed to the matrix converter and the inverter. Therefore, the current rating of a switching device can be reduced according to each output power ratio. Moreover, it is not necessary to include the snubber circuit for the matrix converter because the circuit of battery and inverter works as regenerative snubber circuit for the matrix converter. Therefore, the commutation of the matrix converter can be simplified from four steps to two steps because the pulse timing of the matrix converter may have a dead time period. Consequently, the number of drive circuits of the matrix converter can be reduced from eighteen to nine because the same gate signal can be used for a couple of the switching device in the same arm. However, the matrix converter and inverter are prohibited to be active at the same time because the short circuit occurs between the generator and the battery. Moreover, the battery voltage is constrained to larger than the maximum line voltage of the generator.

IV. THE PROPOSED CONTROL STRATEGY

This paper proposes the control strategy of the matrix converter and inverter system, which does not require interconnection reactors. In addition, we control the output voltage of each converter and the power distribution ratio of the combined system simultaneously. Moreover, the operation time of the matrix converter and the inverter is divided for every carrier cycle so that the input current is held to a sinusoidal wave form.

Fig.6 shows the control block diagram of the proposed combine system. The power distribution ratio is controlled by the operation time division of each converter. The output voltage is obtained by average output voltage of inverter and matrix converter. Thus, a variation triangle carrier, which has difference slope between up and down as reported in [4], is used in order to maintain the sinusoidal input current waveform.

A. *The simultaneous control method for the output voltage and the output power ratio*

Fig.7 shows the relationship between the output voltage and the operation time ratio for the proposed combined system. The output voltage is decided by the average value of the output voltage between the matrix converter and the inverter. Therefore, when the operation time ratio for the matrix converter is defined as α_{mc} and the operation time ratio for the inverter is defined as 1-α_{mc} in one carrier cycle, the output line voltage is obtained by (1).

$$V_{sysout} = \alpha_{mc} V_{mcout} + (1-\alpha_{mc}) V_{invout}$$
$$= \alpha_{mc}\lambda_{mc} E_{generator} + (1-\alpha_{mc})\lambda_{inv} \frac{E_{dc}}{2}\sqrt{\frac{3}{2}} \qquad (1)$$
$$\left(0 \le \lambda_{mc} \le 0.866,\ 0 \le \lambda_{inv} \le 1,\ \sqrt{2}E_{generator} < E_{dc}\right)$$

where, V_{sysout} is the output line voltage of the proposed system, V_{mcout} is the output line voltage of the matrix converter, V_{invout} is the output line voltage of the inverter, λ_{mc} is the modulation index of the matrix converter, λ_{inv} is

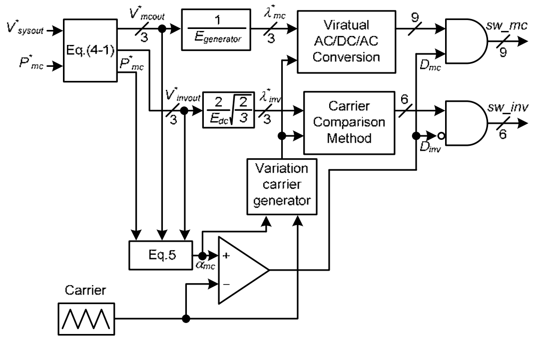

Fig.6 Control block diagram of the proposed system.

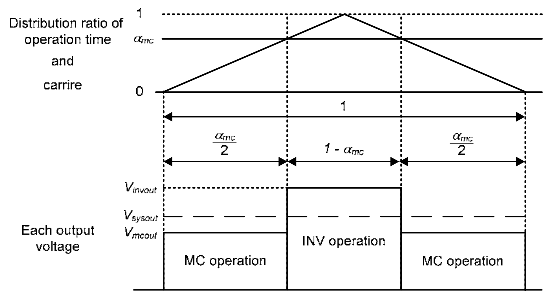

Fig.7 Relationship of the output voltage between the proposed system and each converter.

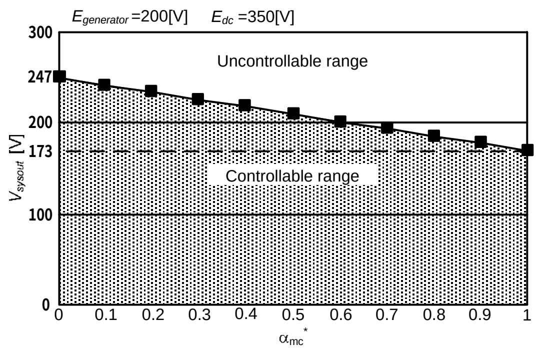

Fig.8 Output voltage range for the proposed system.

the modulation index of the inverter, $E_{generator}$ is the line voltage of the generator, and E_{dc} is the battery voltage.

Fig.8 shows the output voltage range for the proposed system. In the proposed system, the battery voltage is constrained by larger than the maximum line voltage of the generator. Thus, the range of the output voltage is defined from zero volts to battery voltage.

The power distribution ratio is calculated by multiplying the output voltage and operation time ratio. Generally, the instantaneous power from the symmetrical star configuration power supply to the balance star configuration load is given by (2).

$$P = 3VI\cos\varphi \qquad (2)$$

where, P is the output power, V is the output phase voltage, I is the output current, and $\cos\phi$ is the load power factor.

In a proposed system, the load current and the load power factor of the matrix converter are equal to that of the inverter due to the parallel connection. Therefore, the power distribution ratio of the matrix converter is expressed by (3) when the instantaneous power is assumed that the constant during one carrier cycle.

$$P_{mc} : (1 - P_{mc}) = \alpha_{mc} V_{mcout} : (1 - \alpha_{mc}) V_{invout}$$

$$P_{mc} = \frac{\alpha_{mc} V_{mcout} + V_{invout}}{\alpha_{mc}(V_{mcout} - V_{invout})}$$

$$= \frac{2\sqrt{2}\alpha_{mc}\lambda_{mc}E_{generator} + \sqrt{3}\lambda_{inv}E_{dc}}{\alpha_{mc}\left(2\sqrt{2}\lambda_{mc}E_{generator} - \sqrt{3}\lambda_{inv}E_{dc}\right)} \quad (3)$$

where, P_{mc} is the power distribution ratio for the matrix converter, P_{inv} is the power distribution ratio for the inverter, V_{mcout} is the output line voltage of the matrix converter, and V_{invout} is the output line voltage of the inverter.

Thus, the output voltage of the proposed system is constrained by the power distribution ratio. To control the output voltage and the power distribution ratio at the same time, the output voltage command and operation time ratio of the matrix converter is leaded by (4) and (5) from (1) and (3). It is noted that the modulation index of the matrix converter can be calculated by (4-2).

$$V^*_{mcout} = \frac{P^*_{mc} V^*_{sysout} V^*_{invout}}{V^*_{sysout}(P^*_{mc} - 1) + V^*_{invout}} \quad (4\text{-}1)$$

$$\left(0 \le V^*_{mcout} \le 0.866 E_{generator}\right), \left(0 \le V^*_{invout} \le \frac{E_{dc}}{\sqrt{2}}\right)$$

$$\lambda^*_{mc} = \frac{\sqrt{3} P^*_{mc} V^*_{sysout} \lambda^*_{inv} E_{dc}}{E_{generator}\left\{2\sqrt{2} V^*_{sysout}(P^*_{mc} - 1) + \sqrt{3}\lambda^*_{inv} E_{dc}\right\}} \quad (4\text{-}2)$$

$$\left(0 \le \lambda^*_{mc} \le 0.866\right), \left(0 \le \lambda^*_{inv} \le 1\right)$$

$$\alpha_{mc} = \frac{P^*_{mc} V^*_{invout}}{V^*_{mcout} - P^*_{mc}\left(V^*_{mcout} - V^*_{invout}\right)} \quad (5)$$

where, V^*_{mcout} is the output line voltage command for the matrix converter, V^*_{invout} is the output line voltage command for the inverter, V^*_{sysout} is the output line voltage command for the proposed system, λ^*_{mc} is the modulation index for the matrix converter, and λ^*_{inv} is the modulation index for the inverter.

Fig. 9 shows the relation of the output voltage command between the inverter and the matrix converter according to each power distribution ratio when the output voltage command of the proposed system is set to 100 [V]. This figure means that, for example, if the voltage command of the inverter is set to 150V, and the power distribution ratio is set to 0.5, then the matrix converter voltage command have to be set to 75 [V] to obtain 100[V] of the output voltage for the proposed system. The power distribution ratio is independently controlled when the output voltage command of the proposed system equals to each of the converter. However, the voltage command of each converter is restricted by the power distribution ratio in other operation point. It should be noted that each output voltage command should be set to the same value when the system output voltage command is lower than the maximum voltage of each converter.

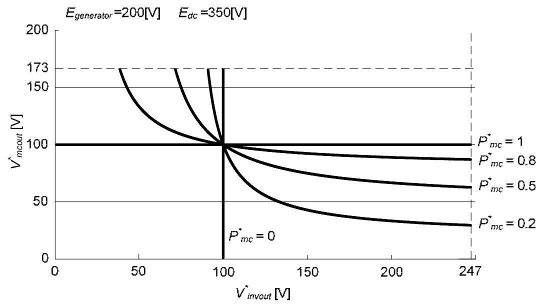

Fig.9 Relation of the output voltage command between the inverter and the matrix converter.

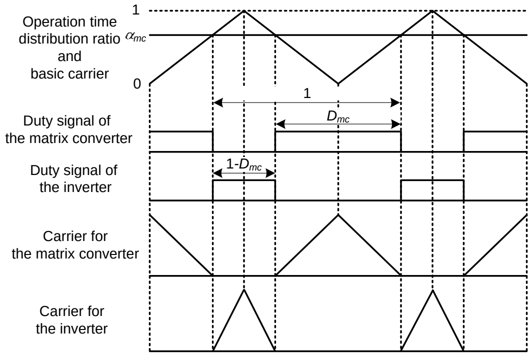

Fig.10 Pulse generation strategy using the variation carrier

B. The generating method of the variation carrier corresponding to the operation time division ratio

Fig.10 shows the pulse generation strategy using the variation carrier in proportion to the operation time ratio. The selected signal of the operation converter is obtained by comparing the operation time ratio command with a basic triangle carrier. During one cycle of the basic carrier, the operation time is distributed the inverter and matrix converter. The relation between the operation time ratio of each converter and the selection can be expressed in (6).

$$D_{mc} : 1 - D_{mc} = \alpha_{mc} : 1 - \alpha_{mc} \quad (6)$$

where, D_{mc} is the operation time ratio of the matrix converter.

Special triangle carriers are made for the each converter during one cycle of the basic carrier. The slope of each special carrier is proportion to each operation time ratio. In the proposed strategy, the change of each converter is achieved at the point of each converter is output a zero voltage vector. This is to avoid the jump and vibration of the output current.

V. SIMULATION RESULTS

Table 1 shows the simulation parameters. The output voltage command of the system is set to 140 [V] constantly, and the power distribution ratio was changed from 0.8 to 0.3 at 100 [ms]. It is noted that the dead time and commutation time of each converter are neglected in order to investigate the basic operation of the proposed system.

Fig.11 shows the output voltage, current and power waveforms of the proposed system. The sinusoidal waveform of the voltage and current are obtained without unexpected jump or vibration at the operation change

TABLE I.
SUMIRATION PARAMETERS

Input AC voltage	200[V]
Input frequency	50[Hz]
DC voltage	350[V]
Output voltage command of the combined system	140[V]
Output voltage command of the MC	140[V]
Output voltage command of the INV	140[V]
Output frequency command	60[Hz]
Output power distribution ratio command(P^*mc)	0.8,0.3
Resistance (load)	5[Ω]
Reactor(load)	5[mH]

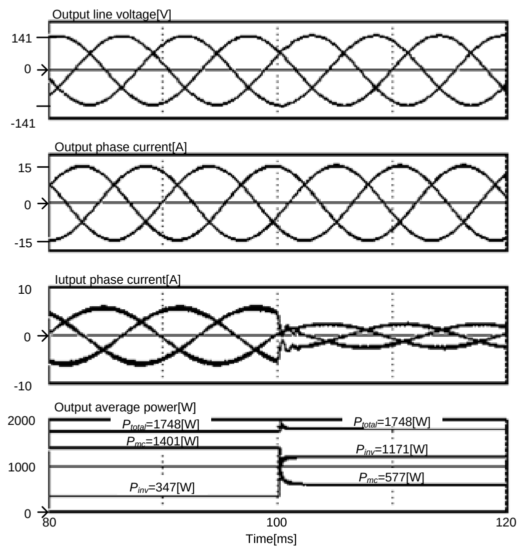

Fig.11 Simulation results of the proposed system

point. Moreover, the power distribution ratio of each converter agrees with the each command.

When the power distribution ratio is 0.8, 0.05[%] and 1.2[%] of the total harmonic distortion (THD) are obtained for the output current and the input current, respectively. After the power distribution ratio is changed from 0.8 to 0.3, 0.6[%] and 1.1[%] of the THD are obtained for the output current and the input current, respectively.

VI. EXPERIMENT RESULTS

Fig.12 shows the configuration of the experimental system in order to confirm the basic operation. The battery is simulated by the combination of a variable AC regulator and a diode rectifier. The generator is also simulated by a variable AC regulator.

Table 2 shows the experiment parameters. The power distribution ratio was set equal to the operation time division ratio in order to clarify the relation between the output voltage of the proposed system, the power distribution ratio of the each converter and the operation time division ratio and the harmonic distortion of the current.

Fig.13 shows the waveform of the output voltage, and output current, and the input current during a single operation of the matrix converter (MC). The output

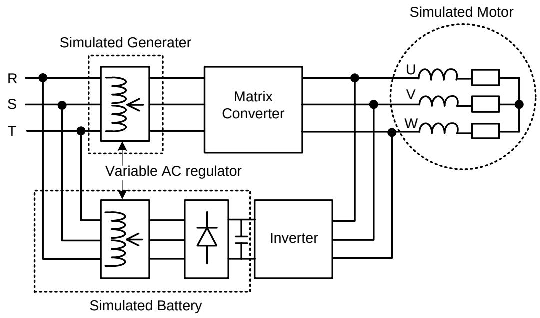

Fig.12 The configuration of the experimental system.

TABLE II.
EXPERIMENT PARAMETERS

Input AC voltage	140[V]
Input frequency	50[Hz]
DC voltage	255[V]
Output voltage command of the combined system	90[V]
Output voltage command of the MC	90[V]
Output voltage command of the INV	90[V]
Output frequency command	35[Hz]
Dead time	2.5[μs]
Output power distribution ratio command(P^*mc)	0~1
Resistance (load)	12.5[Ω]
Reactor(load)	5[mH]

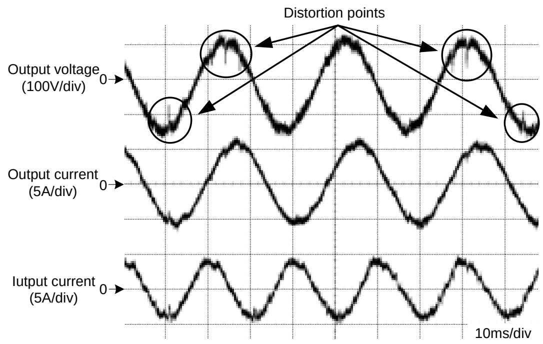

Fig.13 The waveform of the output voltage, the output current, the input current when the single operation of the matrix converter.

voltage is only observed by using the low pass filter set cut-off frequency of 1 kHz. 1.63[%] and 1.2[%] of the THD are obtained for the output and input current, respectively. The output power is 628[W]. The output voltage waveform has been distorted by the commutation error as shown in Fig.13. It is noted that the commutation error of the proposed system is the same as the conventional matrix converter. That is, a conventional commutation error compensation method as proposed in [14] can be applied.

Fig.14 shows the waveform of the output voltage and output current during single operation of the inverter (INV). 2.55[%] of The THD is obtained for the output current at 628[W] of the output power.

Fig.15 shows the waveform of the output voltage, current and the input voltage when the power distribution ratio command is set to 0.5. Each input-and-output waveform can be controlled to sinusoidal wave. The THD of the input current is 3.9[%]. However, the THD of the output current is 9.62[%], and has deteriorated compared with the case where only each converter operates. One of

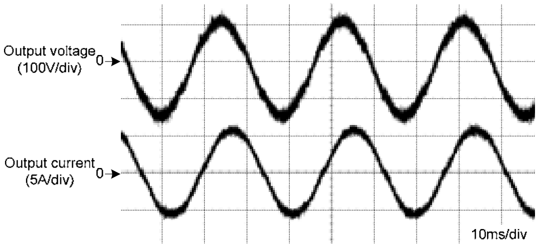

Fig.14 The waveform of the output voltage and the output current when the single operation of the inverter.

the reasons of increasing the THD is the voltage error between the inverter and the matrix converter.

Fig.16 shows the relationship between the output voltage and the power distribution ratio of the proposed system. The dotted line indicates the ideal value, and the black spot indicate the measurement values. The output voltage of the proposed system decreases when the power distribution ratio command is larger than 0.4 as shown in Fig.16. The cause of this result is also the voltage error by the dead-time of the inverter and the commutation of the matrix converter.

Fig.17 shows the comparison between the ideal value and the measurement value of each output power. The measured output power agrees well with the power command. However, the measurement value of each output power decreases more than the ideal values when the power distribution ratio command is larger than 0.4. The reason is because the decrement in the output voltage of the proposed system described in Fig. 16. Therefore, if the decrement of output voltage of the proposed system can be improved, the output power can follow the power command, too.

Fig.18 shows the relationship between the power distribution ratio, the THD of the output and input current. The THD of the output current becomes 5[%] or less, all the power distribution ratios. On the other hand, the THD of the input current become less than 15% at over 0.2 of the operation time ratio of the matrix converter. The reason can be explained that the fundamental component of the input current against an input filter current is decreased when the input current is decreased in the small operation time ratio. However, the distortion component is almost the same. That is, the THD is increased relatively because the distortion component was not changed but the fundamental component is decreased.

VII. CONCLUSION

This paper proposed a control strategy of a matrix converter and an inverter parallel system with no requires of interconnection reactors. In the proposed system, the operation time of each converter was divided by every carrier cycle, and the output power of each converter and the output voltage of a proposed system were controlled simultaneously. The input current also was controlled to the sinusoidal wave.

The features of the proposed system are as follows:

i) By using the proposed control strategy, Interconnection reactors and transformers for a parallel multiplexing system become unnecessary.

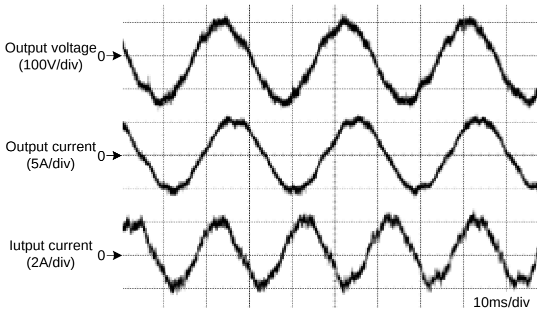

Fig.15 The waveform of the output voltage, the output current and the input current when the output power distribution ratio command is 0.5.

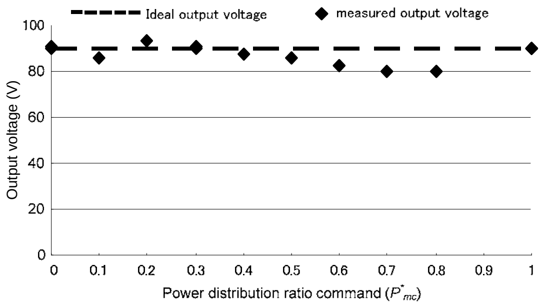

Fig.16 The relationship between the output voltage and the output power distribution ratio of the proposed system.

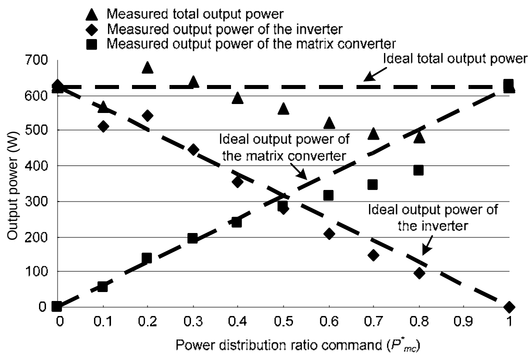

Fig.17 The comparison between the ideal output power value and the measurement value of each output power.

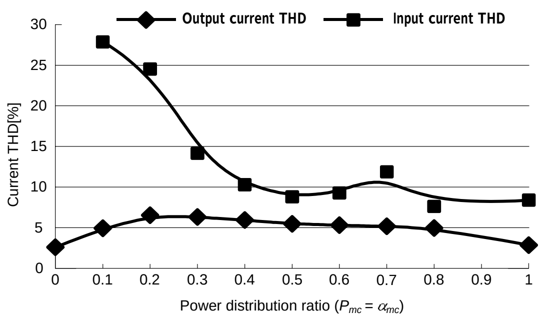

Fig.18 The relationship between the output power distribution ratio and the THD of input and output current.

ii) The current rating of IGBT can be reduced according to the output power ratio of each converter.

iii) The drive circuits of the matrix converter are reducible from eighteen to nine because the commutation of the matrix converter can be simplified from four steps to two steps.

iv) The combined system can be miniaturized because a special snubber circuit for matrix converter is not need to be added.

The utility of the proposed control method was confirmed by the simulation and the experiment, and the good results were obtained. In the future works, the dead time error correction for the variation carrier will be examined to improve the THD of the output and input voltage, the input current.

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