Combination of Input/Output Control using Matrix Converter for Islanded Operation for AC generator

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***Abstract*—This paper proposes a control method of a matrix converter in a micro grid system to obtain stable islanded operation. The islanded operation using a matrix converter needs a voltage feedback control to assume the matrix converter as a constant voltage power supply for the load. On the other hand, the islanded operation also requires a generator current control with a feedback to determine provided power. However, when the matrix converter is applied two feedback controls on the generator side and the load side, the interference between both controls occurs and the matrix converter becomes unstable. This instability occurs due to difference of instantaneous active powers between the generator side and the load side; therefore, the active power is determined by the voltage source converter only. The active current which is needed to control the filter capacitor voltage should be converted to the generator current command as an active power command. Thereby, the proposed control method avoids the interference, and achieves a stable islanded operation. In addition, the proposed control also offers a constant three-phase voltage to the load even if the load power is light because of a compensation of a reactive current into the filter capacitor. As a result, the proposed control method achieves stable islanded operation and unity displacement power factor of the load side. The load current THD (Total harmonic distortion) is 1.4%, and the filter capacitor voltage THD is 1.5%. In the experiment, the load voltage is a sinusoidal waveform of 200 V. In addition, the load voltage THD is 4.56%. Therefore, it is confirmed that the proposed control method achieves stable operation without the interference. This paper confirms validity of the proposed control in the islanded operation by simulation and fundamental experiment.**

Keywords—islanded operation; matrix converter; micro grid

I. INTRODUCTION

Recently, a matrix converter, which directly converts AC power supply voltage into AC voltage of variable amplitude and frequency without large energy storage such as electrolytic capacitor, has been actively studied [1-3]. A matrix converter has advantages over a conventional BTB (back to back) system which is composed of a PWM rectifier and a PWM inverter on the following aspects; size reduction, light-weight, long-life and high efficiency power supplies. These indexes are very important for renewable energy systems

Matrix converters can be applied in generation systems, such as a wind turbine generators, micro-hydro power plant, bio-diesel engine generator, and so on [4]. Lately, it also has been considered to apply a matrix converter to a micro grid system and distributed generation system. In these applications, the generator is commonly connected as an input voltage source of matrix converters [5-6]. In addition, micro gird systems consist of distributed generators and loads in small area such as a remote island which cannot interconnect commercial grid. Thereby, matrix converters in the micro grid need a capability of an islanded operation to continue delivering power from the generator to the load [7].

However, a matrix converter in an islanded operation has a problem. In this application, matrix converters need a voltage feedback control to guarantee reliability as a constant voltage power supply for the load. On the other hand, the matrix converter also requires a generator current control with a feedback to determine provided power. Due to these two feedback controls, the interference between both controls occurs and leads to instability of the matrix converter [8]. The instability is triggered because instantaneous active powers of the input and output sides are determined by both controls independently. However, a matrix converter does not have energy storages; therefore, a matrix converter becomes unstable because of the difference between both instantaneous active powers. However, solutions for this issue have been reported rarely.

Previous studies regarding the island operation using a matrix converter have been discussed in [6] and [8]. In past work, a matrix converter is connected to a generator and a motor [8]. This work achieves controls of a generator current and an output voltage in the islanded operation. However, the generator should be used in high speed region only because the high voltage side of a matrix converter is connected to the generator. In addition, the terminal voltage of the generator and the input current are unstable due to a filter resonance between the synchronous reactance of the generator and the input capacitor. Thereby, the control is more complex due to suppressing control for the filter resonance. On the other hand, a matrix converter for a distributed generation achieves islanded operation [6]. This work achieves the islanded operation at rated power. However, this work does not confirm the operation in area of light load.

In this paper, in order to solve problem about the instability, a control method for the islanded operation in a matrix converter is proposed. The proposed method has two feedback controls for the filter capacitor voltage and the generator current. However, the instability is avoided because the proposed method combines these feedback controls and only the generator current control determines the active power of the converter. As a result, the interference is not triggered and a stable islanded operation obtained. In addition, the proposed control compensates an effect of a reactive current into the filter capacitor and offers a constant three-phase voltage to the load even when the load power is light. In this paper, the stability of islanded operation is evaluated in simulation and fundamental experiment.

II. Circuit Configuration and Control Strategy

A. Circuit configuration

Fig.1 shows a circuit diagram of an interface converter between a generator and a load using a matrix converter. In this system, a low voltage side of the matrix converter is connected to the generator, and high voltage side is connected to the load. By this connection, the generator is utilized in wide speed region though the opposite connection restricts the generator operation in high speed region only. A matrix converter requires LC filter in the load side to eliminate harmonic current due to switching operation.

B. Virtual AC-DC-AC conveter control method

In order to simplify the control techniques, a virtual AC-DC-AC conversion technique which has been discussed in [9] is referred.

Fig.2 shows an equivalent circuit of the matrix converter in Fig.1 using an AC-DC-AC converter, which is based on the virtual AC-DC-AC conversion technique. In Fig.1 and Fig.2, the input voltage is represented as $^t[v_r,v_s,v_t]$ and the output voltage is represented as $^t[v_u,v_v,v_w]$. S_{xy} represents the switching function of the switches, when S_{xy} is turned on, S_{xy} =1 and when S_{xy} is turned off, S_{xy} =0. According to the virtual AC-DC-AC conversion theory, the PWM pattern for the matrix converter can be converted by the following equation.

$$\begin{bmatrix} S_{ru} & S_{su} & S_{tu} \\ S_{rv} & S_{sv} & S_{tv} \\ S_{rw} & S_{sw} & S_{tw} \end{bmatrix} = \begin{bmatrix} S_{up} & S_{un} \\ S_{vp} & S_{vn} \\ S_{wp} & S_{wn} \end{bmatrix} \begin{bmatrix} S_{rp} & S_{sp} & S_{tp} \\ S_{rn} & S_{sn} & S_{tn} \end{bmatrix} \quad (1)$$

As a result, control performance of the matrix converter is exactly same as the AC-DC-AC converter because the relationship between input voltage and the output voltage is the same. It should be noted that the relationship between input current and output current is also the same. Thus, the switching pulses of the matrix converter are generated easily because the proposed control method can considered with a voltage source converter and a current source inverter.

C. Control strategy of islanded operaiton

Fig.3 shows a PWM pulse generator based on the virtual AC-DC-AC conversion technique. This diagram combines switching pulses generated by a virtual converter and a virtual inverter controls and synthesizes switching pulses of the matrix

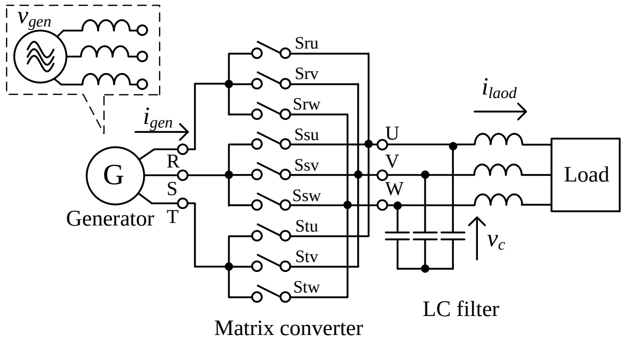


Fig. 1. Interface converter between a generator and a load using matrix converter

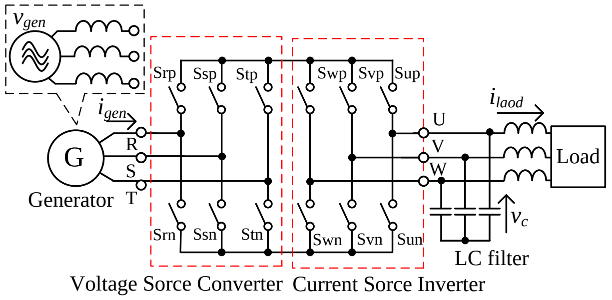


Fig. 2. Equivalent circuit using AC-DC-AC converter. This circuit is used based on the virtual AC-DC-AC conversion technique in order to simplify the control techniques.

converter according to (1). The voltage source converter control is fed input voltage command v_r*, v_s*, v_t* from the generator current control. Similarly, the current source inverter control is fed output current command i_u*, i_v*, i_w* from the filter capacitor voltage control on the load side. Then, the virtual converter is applied discontinuous PWM method for improvement of a voltage transfer ratio. In contrast, the virtual inverter uses single leg modulation [9].

Fig.4 shows the proposed control block diagram for the islanded operation. The proposed control method is based on d-q frame because the d-q frame defines the d-axis as a reactive component and the q-axis as an active component although the generator frequency is different from the grid frequency. Thereby, the active power is simply controlled on the d-q frame.

Fig.4(a) shows a control block diagram of the generator current control. This control is for determining the instantaneous active power from the generator and this control uses a feedback controller as well as a voltage source converter due to applying the virtual AC-DC-AC conversion technique. Then, θ_{gen} is a rotor angle of the generator, i_r, i_s, i_t are detected value of three phase generator current, v_r*, v_s*, v_t* are input voltage command for the voltage source converter, and P_{load}* is active power command from the filter capacitor voltage control on the load side. ϕ_{fe} is back-emf constant of generator. θ_{gen} is determined by integrating the generator rotation speed ω_{gen}. An ACR (Auto current regulator) block has a PI regulator in order to control the generator current i_{dgen}, i_{qgen}. In the case, the d-axis generator current command i_{dgen}* is always fixed to 0 p.u. for achieving unity input displacement power factor. Furthermore, the q-axis current i_{qgen}* is calculated by the active power and detected q-axis induced voltage of the generator.

Fig.4(b) shows control block diagram of the filter capacitor voltage control on the load side. This control is for the islanded operation which assumes the matrix converter as a constant voltage power supply to the load. This control employs a feedback controller as well as a current source inverter due to applying the virtual AC-DC-AC conversion technique. Then, v_u, v_v, v_w are detected filter capacitor voltage, i_u*, i_v*, i_w* are output current command for the current source inverter, and θ_{load}* is phase angle of the load current. In order to supply the generator power to the load as well as a grid, θ_{load}* is determined by integrating the grid frequency. An AVR (Auto voltage regulator) block has a PI regulator in order to control the load voltage. In the case, the d-axis load voltage command v_{dload}* is always fixed to 0 p.u. for achieving unity output displacement power factor. On the other hand, output of the q-axis AVR is not used in the current source inverter and the q-axis current command i_{qload}* is set to 1. This is to avoid the interference of the active power between the generator current control and the filter capacitor control and the principle is as following.

The active current command i_{qload}* is needed to control the q-axis voltage of the filter capacitor v_{qload}. However, if the current source inverter is fed the active current command i_{qload}* from the feedback controller, the feedback controls of the generator side and the load side determine each required active power independently. This is because the generator current control decides the input voltage command with referring the generator current and the filter capacitor voltage control decides the output current command with referring the filter capacitor voltage, which is equivalent to determine the instantaneous power. Thus, because of the difference between both required instantaneous active powers, the matrix converter becomes unstable. In order to avoid the interference, the active current command of the current source inverter should be fed with an open loop as shown in Fig.4(b), which does not contribute to the active power. As a result, the active power is determined by the voltage source converter only and a stable islanded operation is achieved.

In contrast, a reactive power does not exist in DC link. Thereby, the power transmitted between the generator and the load through the matrix converter is only active component, as shown in Fig.2. Hence, the active current which is needed to control the filter capacitor voltage should be converted to the generator current command as an active power command. Therefore, Fig. 4 uses the active power command P_{load}*.

Moreover, the output of the d-axis AVR adjusts the output power factor of the matrix converter because the d-axis current command of the current source inverter affects the reactive current. Thus using the output of the d-axis AVR is equivalent to compensation of the reactive current caused by the filter capacitor and this compensation contributes to supplying a constant voltage to the connected load at the light load area in the islanded operation.

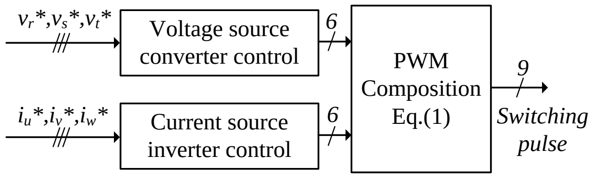
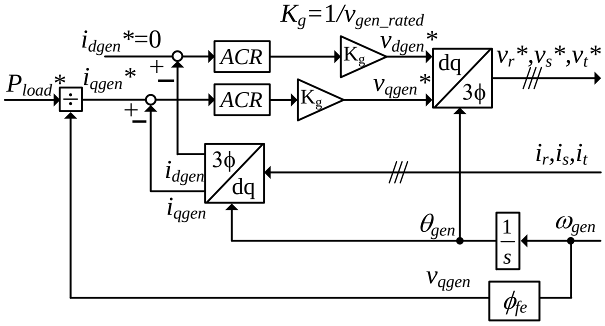
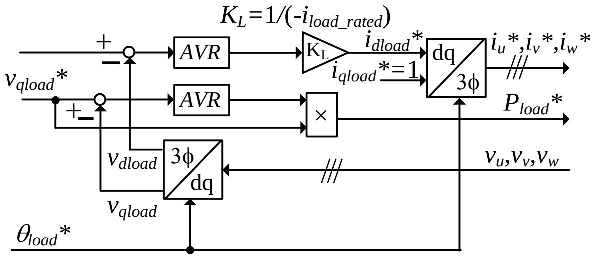


Fig. 3. Switching pulse generator



(a) Generator current control



(b) Filter capacitor voltage control on the load side

Fig. 4. Control block diagram for islanded operation. This diagram is separated into the generator current control and the filter capacitor voltage control on the load side. This control obtains stability for islanded operation without interference between the feedback controls on the generator and the load sides.

III. Simulation Result

The simulation parameters are as follows, the generator induced voltage is 100V (line to line), the frequency of a generator is 50Hz, the switching frequency is 10 kHz, and the cut-off frequency of LC filter is 1 kHz. Note that the simulation is running in a RL load condition.

Fig.5 shows the generator side and the load side waveform in steady state with the interference between the generator current and the filter capacitor voltage controls. In this simulation, the generator current control and the filter capacitor voltage control work independently. The load resister is 26.6 Ω and the load inductor is 2.55 mH (3%). This simulation confirms unstable islanded operation without the proposed control method. In this simulation, the active powers of the generator side and load side are independently determined by both controls As a result, the load current and the filter capacitor voltage is not sinusoidal waveform and these waveforms have distortion. Thereby, the operation of the matrix converter is instability.

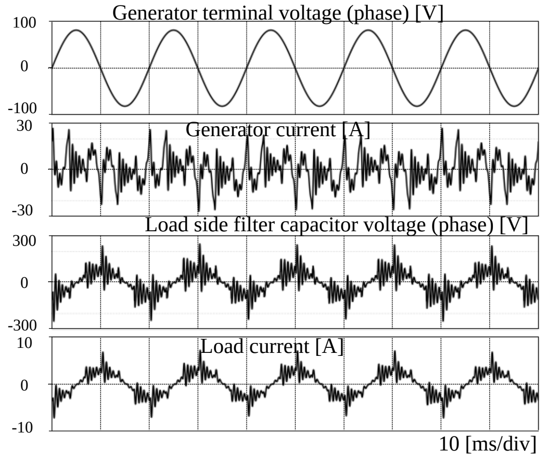


Fig.5. Simulation results of the islanded operation without proposed control. This waveform is unstable due to the interference.

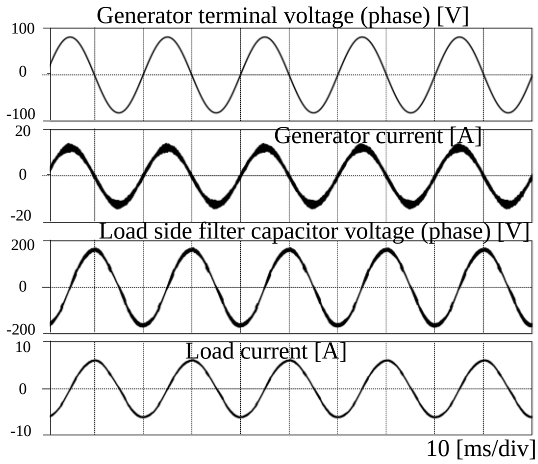


Fig.6. Simulation results of the islanded operation with proposed control in steady state at rated power.

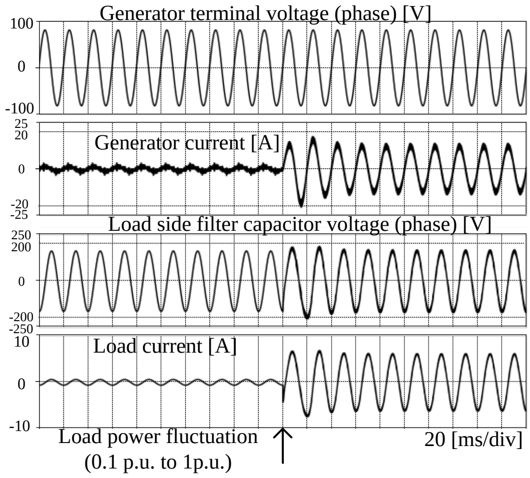


Fig.7. Simulation results of a load fluctuation under the islanded operation. The load power is changed from 0.1 p.u. to 1 p.u.

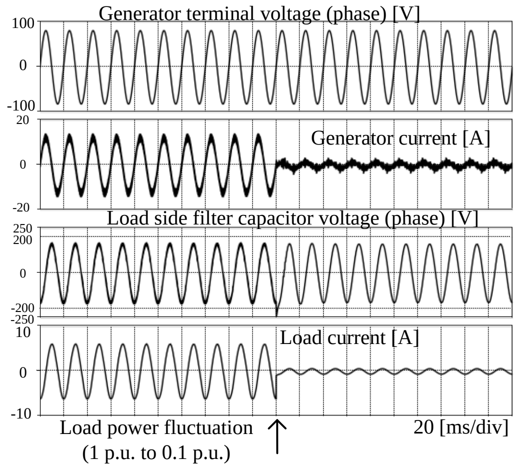


Fig.8. Simulation results of a load fluctuation under the islanded operation. The load power is changed from 1 p.u. to 0.1 p.u.

Fig.6 shows the generator side and the load side waveform in a steady state with the proposed control method. The load resister is 26.6 Ω and the load inductor is 2.55 mH (3%). In addition the matrix converter outputs 1.5kW (1p.u.). As a result, the film capacitor phase voltage is sinusoidal wave and this RMS voltage value is 115 V (line to line voltage is 200 V.). The generator current THD (Total Harmonics Distortion) is 0.8%, the load current THD is 1.4%, and the film capacitor voltage THD is 1.5%. The proposed control method achieves unity displacement power factor of the generator side and the load side. These results lead to a conclusion that the proposed control obtains the stable islanded operation.

Fig.7 and Fig.8 show the generator side and the load side waveform in a load fluctuation by changing a load resister. In Fig.7, the load resister value is changed to 266 Ω from 26.6 Ω. The output power of the matrix converter changes to 0.15 kW (0.1p.u.) from 1.5kW (1p.u.). In Fig.8, the load resister value is changed to 26.6 Ω from 266 Ω. The output power of the matrix converter changes to 1.5 kW (1p.u.) from 0.15kW (0.1p.u.). As results, although the output power is varied, the output voltage is maintained to a constant voltage of 115 V except a transient state regardless the load power. This is because of the compensation of the reactive current caused by the filter capacitor. Thereby, the validity of the proposed control method is confirmed.

IV. Experimental Results

Table 1 shows experimental parameters. The proposed method is based on a virtual AC-DC-AC conversion technique. Therefore, the parameters of ACR and AVR are designed as well as conventional design methods in a voltage source inverter and a current source converter. Fig.9 shows a circuit diagram of the matrix converter in an experiment. In Fig.9, a magnetic contactor is added to separate the grid connected operation and the islanded operation. The generator is replaced with a three-phase voltage source of 100 V and input inductors in order to simplify the experiment.

A. Grid connected operation

In the grid connection operation, an open loop control is applied to the grid side of the matrix converter. The q-axis input current command i_{qgen}* is fed by an open-loop control instead of P_{load}* and the d-axis output current command i_{dload}^* is set to zero. Additionally, in order to connect the grid, the magnetic contactor is closed.

Fig.10. shows the input and the output waveform in the grid connected test. The generator current and the grid current are sinusoidal waveform with the THD of 4.88% and 8.65%, respectively. In addition, the matrix converter operates in the unity displacement power factor on the generator and the grid sides because i_{dgen}^* and i_{dload}^* are zero. As a result, it is confirmed that the matrix converter achieved stable operation in grid connected operation.

B. Islanded operation

In the islanded operation, the proposed control method is applied to the matrix converter in order to obtain a stable operation without the interference. By opening the magnetic contactor, the matrix converter is separated from the grid.

Fig.11 shows the input and the output waveform in the islanded operation when a load resister R_{load} is 32.5 Ω (1.22 p.u.). In this case, the matrix converter outputs approximately 1-kW power (0.66p.u.). The load voltage is sinusoidal waveform of 200 V owing to the filter capacitor voltage control. In Fig. 11, the generator current THD is 4.94%, the load voltage THD is 4.56%. In addition, the displacement power factors on the generator side and the grid side are unity. As a result, it is confirmed that the proposed control method achieves a stable operation and a load voltage control without the interference.

Fig.12 shows the input and output waveform in the islanded operation when a load resister R_{load} is 75 Ω (2.81 p.u.), which is lower power than Fig. 11. The matrix converter outputs approximately 0.5-kW power (0.33p.u.). By the proposed method, the load voltage becomes a sinusoidal waveform of 200 V in the same manner as Fig. 12. However, the generator current and the load voltage distortion contain more because the filter capacitor is small and the bandwidth of the filter capacitor voltage control is limited. This will be improved in the future by establishing a design method of the PI controller and the LC filter. Therefore, the proposed method achieves a stable operation without depending on a load power.

V. CONCLUSION

This paper discusses a control method for the islanded operation using a matrix converter. In order to guarantee reliability as a constant voltage power supply for the load, the load voltage control is applied. In addition, the generator current to determining control to determine provided power is also introduced. However, these two feedback controls may cause unstable operation because of the interference between both controls in terms of the active power. In order to solve this problem, this paper proposes a control which combines the generator current control and the load voltage control, and the generator current only decides the active power due to avoid interference of difference of instantaneous active powers between the generator side and the load side. As a result, the proposed control method avoids the interference, and achieves the stable operation of the islanded operation. In simulation result, proposed control method achieves stable islanded operation. The load current THD is 1.4%, and the film capacitor voltage THD is 1.5% at rated load. In addition, in order to compensate a reactive current into the filter capacitor, the proposed method offers a constant three-phase voltage to the load even when the load power is light. In the experiment, it is confirmed that the proposed control method achieves the stable operation and the load voltage control without the interference. Then, the generator current THD is 4.94%, the

TABLE I. EXPERIMENTAL PARAMETER

Genrator voltage	100 V_{rms}	Grid voltage	200 V_{rms}
Generator frequency	50 Hz	Grid frequency	50 Hz
Input L	3.0 mH (3.5%)	Filter L (%Z)	2.2 mH (2.6%)
K_p(ACR)	1.38 p.u.	Filter C (%Y)	4.5μF (3.8%)
T_i(ACR)	21.1 ms	Dampng resister (Damping Factor)	47 Ω (0.24)
K_p(AVR)	0.05 p.u.	Output power	1.5 kW
T_i(AVR)	4.67ms	Carrier frequency	10 kW

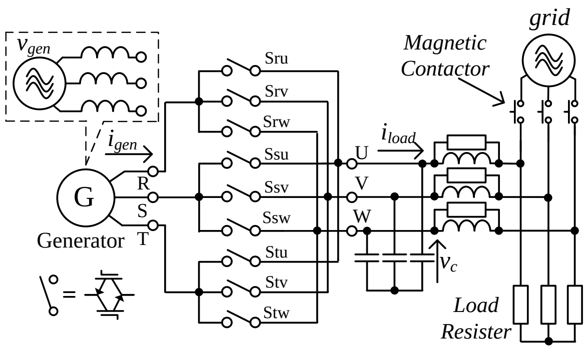


Fig. 9. Experimental circuit diagram. The operation mode is switched by the magnetic contactor.

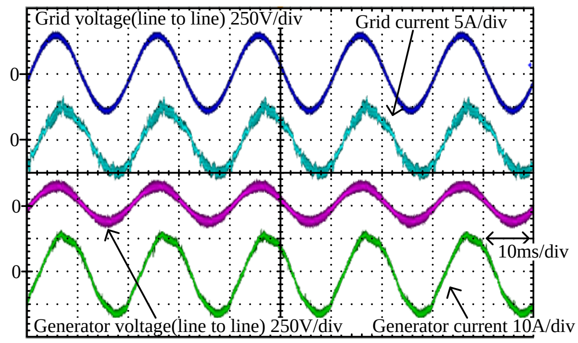


Fig. 10. Experimental results of the grid connected test in steady state. The generator supplies power to the grid through the matrix converter.

load voltage THD is 4.56%, and the load current THD is 4.94%. From these results, the validity of the proposed control method for the islanded operation is demonstrated.

In the future, usefulness of the proposed method will be confirmed in the islanded operation when a nonlinear load such as a diode rectifier is connected.

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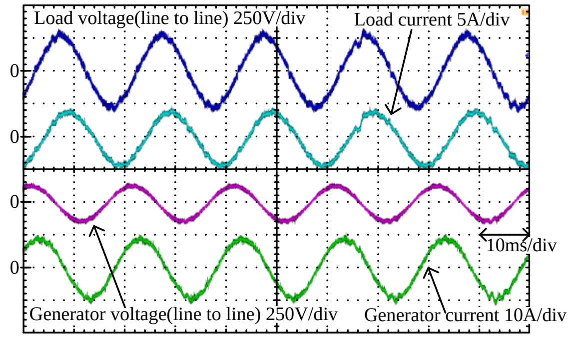

Fig. 11. Experimental results of the islanded operation in steady state with R_{Load}=37.5Ω. The load voltage is sinusoidal waveform of 200 V.

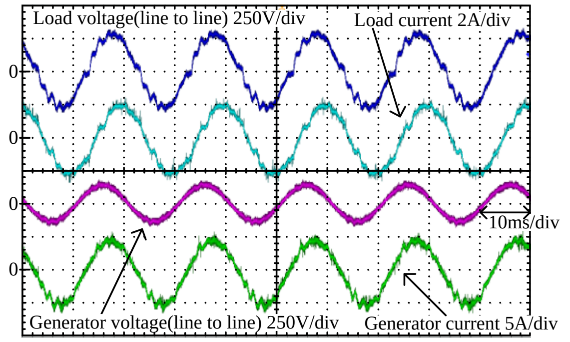

Fig. 12. Experimental results of the islanded operation in steady state with R_{Load}=75Ω. The proposed method achieves stable operation without depending on the load power